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16. Abstract

The fuel savings potential of advanced turboprops (operational about 1985) was calculated and compared with that of an advanced turbofan for use in an advanced subsonic transport. At the design point, altitude 10.67 km and Mach 0.80, turbine-inlet temperature was fixed at 1590 K while overall pressure ratio was varied from 25 to 50. The regenerative turboprop had a pressure ratio of only 10 and a 85 percent effective rotary heat exchanger. Variable camber propellers were used with an efficiency of 85 percent. The study indicated a fuel savings of 33 percent, a takeoff gross weight reduction of 15 percent, and a direct operating cost reduction of 18 percent was possible when turboprops were used instead of the reference turbofan at a range of 10 200 km. These reductions were 28, 11, and 14 percent, respectively, at a range of 5500 km. Increasing overall pressure ratio from 25 to 50 saved little fuel and slightly increased takeoff gross weight.

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SUMMARY

The fuel savings potential of advanced turboprops (operational about 1985) was calculated and compared with that of an advanced turbofan for use in an advanced subsonic transport. All the engines were designed for cruise at 10.67 km (35 000 ft) with a turbine-rotor inlet temperature of 1590 K (2960 R). The regular turboprops had overall pressure ratios of 25 and 50. However, the regenerative turboprop had an optimum pressure ratio of only 10, and a ceramic rotary heat exchanger which had a design effectiveness of 85 percent and a pressure loss and leakage of 4 percent. The propeller efficiency was assumed to be 85 percent which implies an advanced low camber or variable camber propeller technology for the high cruise speeds studied (Mach 0.65 to 0.90). The mission called for a payload of 18 144 kg (40 000 lb) at a range of 10 200 and 5500 km (5500 and 3000 n. mi.). As gross weight changed, wing, landing gear, and engine weight all varied while the fuselage size and wing loading were fixed. The drag due to the changing propulsion systems and wing size was taken into account.

The reference turbofan in this study used about 22 percent less fuel than a current turbofan if used on the same aircraft. The results of this study indicate that, relative to the reference turbofan, the turboprops saved 31 to 33 percent of the fuel on the long range mission and about 27 to 28 percent on the medium range mission. With the high propeller efficiencies assumed, the direct operating cost comparison at Mach 0.80 is also favorable toward the turboprop by 14 to 18 percent. The minimum direct operating cost occurs at about Mach 0.76 for both engine types. These important benefits for the turboprop engine are not substantially reduced by rather pessimistic perturbations in the propeller, gearbox, and heat exchanger assumptions. The regenerative turboprop cycle yields about the same fuel and takeoff gross weight results as the best regular turboprop. The direct operating cost is worse, however, due to the cost of the heat exchanger.

INTRODUCTION

It seems only reasonable in this time of energy conservation mindedness, that some thought should be given to reducing aircraft use of fuels. Today, aircraft are totally dependent on the oil supply for their fuels and United States civil aircraft now use about 3.8 percent of that oil. Projections taken from reference 1 indicate that by 1984 the United States Certified Air Carriers will double their revenue passenger miles. In the same time, the jet fuel used by these carriers is estimated to increase by 50 percent. Fuel conservative aircraft could reduce fuel demand substantially. To this end, industry and government agencies are studying the problem. An example of this type of work is reported in reference 2, which was done for STOL transports. The turboprop in reference 2 showed a 38-percent savings in fuel compared to a turbofan. Other references on the subject are 3, 4, 5, and 6. In reference 6 the author estimates that the optimum turbofan has a bypass ratio of 10.4, an overall pressure ratio of 40, and a fan pressure ratio of 1.6 at a noise goal of FAR-10 dB. It is also estimated that the optimum turbofan used 22 percent less fuel than a current high bypass turbofan if it were installed on the same type of aircraft. Some of the references listed differ in results and conclusions, but all testify to the search for ways to save fuel. Many were written before the cost of fuel increased so rapidly in late 1973 and early 1974, and the full impact of present day fuel cost was not factored into their conclusions.

There are several ways to reduce commercial airline use of fuel. Flying slower reduces fuel consumption as does restricting flight frequency which forces load factors up. Improvements are possible to existing engine and aircraft that would reduce fuel consumption. Finally, an entirely new aircraft, engine, or both could possibly result in fuel savings. The purpose of this study is to investigate the fuel saving potential of two types of new engines on an advanced aircraft.

The two engine types are: (1) turboprops using advanced propellers, and (2) regenerative turboprops. The design turbine inlet temperature at cruise was fixed at 1590 K (2960 R). The regenerative turboprop was designed at an overall pressure ratio which minimized specific fuel consumption. The regular turboprops were designed at overall pressure ratios of 25 and 50 in order to show the potential of cycle pressure ratio increases. The basic study was done at a cruise Mach number of 0.80 and 10.67 km (35 000 ft). However, the design Mach number was varied from 0.65 to 0.90 to show the effects on fuel consumption, takeoff gross weight, and relative direct operating cost. The effect of varying propeller efficiency was also investigated. Primary aircraft design parameters such as

wing sweep, thickness ratios, and aspect ratio were scheduled with design Mach number. Two ranges were investigated: medium range 5500 km (3000 n. mi.), and long range 10 200 km (5500 n. mi.). The aircraft wings were resized in each case such that wing loading was held constant at 5980 N/m^2 (125 lb/ft^2). The payload remained constant at 200 passengers (18 144 kg (40 000 lb)). Engine size was varied so that its effect could be seen. The drag associated with different types and sizes of engine installations was accounted for.

SYMBOLS

AR	aspect ratio
BPR	bypass ratio
Cl_0	lift coefficient at minimum drag
camber	camber of airfoil
D_{matrix}	diameter of matrix drum, m
D_{ref}	reference diameter of matrix drum, m
L_{matrix}	length of matrix drum, m
L_{ref}	reference length of matrix drum, m
OPR	overall pressure ratio
RTP	regenerative turboprop
TF	turbofan engine
TOGW	takeoff gross weight
TP	turboprop engine
T_4	turbine-rotor-inlet temperature, K (R)
t/c	thickness to cord ratio of the wing
ϵ	effectiveness of the rotary heat exchanger

Subscripts:

ref	reference value of engine
10	OPR = 10 to 1
25	OPR = 25 to 1
50	OPR = 50 to 1

METHOD OF ANALYSIS

Mission

In each mission, the assumptions were as shown in figure 1. Taxi-out was 9 minutes at idle and takeoff was 1 minute at full power. The climb, cruise, and letdown accounted for the total range. Taxi-in was 5 minutes at idle. The reserves consisted of 1 hour at the final cruise fuel rate, 2 minutes at full power for missed approach, and an alternate mission at a lower speed and altitude. The range of the alternate mission was 370 km (200 n. mi.) for the medium range mission and 550 km (300 n. mi.) for the long range mission. The cruise speed of the reference aircraft was Mach 0.80 at 10.67 km (35 000 ft). The payload was assumed to be 18 144 kg (40 000 lb) on all aircraft. Cruise Mach number was varied from 0.65 to 0.90.

Aircraft

Aircraft layouts. - Figures 2(a) and (b) are sketches of aircraft showing the general layout and engine placement. The sketches are meant to be representative of the aircraft types studied but not precise drawings. In the case of the regenerative turboprop (RTP), the aircraft would look much the same as a regular turboprop (TP) except the engines would definitely be longer and wider. Advanced technology could provide propeller of smaller diameter than assumed in this study. In that case, the aircraft would almost certainly be a more conventional low wing design.

Aircraft drag. - The assumptions that went into calculating the drag of the aircraft are shown in table I versus design Mach number. These characteristics are typical for the type of aircraft studied in this report. Figure 3 shows the drag polars for a TF powered 4-engine transport designed at various Mach numbers with a design range of 5500 km (3000 n. mi.). The reference aircraft had engines with a BPR of 10.4 and an OPR of 40. The polars were generated by the AMAC program which is an undocumented in-house code that calculates the airplane size, component weights, drag, mission fuel, and DOC. When engine types are switched in the flight deck, the drag of the reference engines was subtracted and the drag of the new engines was added as if they were isolated engines.

Aircraft and engine weights. - Table II gives a breakdown of the reference long range aircraft weights as calculated by the Aircraft Mission Analysis Code (AMAC). The bare engine weights were calculated by the method of reference 7. The only exception to this was the TP gas generators. The relationship in reference 7 can be used to calculate the weight of a small turbojet but not a turboshaft gas generator. It was found by comparison with known turboshaft

gas generator weights that the reference 7 equations can be used to calculate the weight of turboshaft gas generators if it is assumed the engine is a turbojet instead and the resulting weight is tripled. This large weight penalty for the TP gas generator is due to the large power turbine, the extra shaft and bearings, and a larger and stronger case needed for the larger structural loads. The installed weights include the bare engine plus engine accessories, controls, starting system, fuel system, thrust reversers, propeller, and gearbox. As the engine size was varied in the flight deck, the TOGW varied. This in turn resulted in a change to the wing and landing gear weight. The fuselage remained fixed because the payload remained fixed.

Types of Engines

Two types of engines were studied, the TP, and the RTP. Sketches of these two engines are shown in figure 4 along with a sketch of a reference TF. The TF is normally hung below the wing on a pylon. A TP can be mounted a number of ways. They are commonly mounted flush with the top or bottom of the wing. Since a RTP would be longer than a regular TP, a larger part of the nacelle would probably be attached to the wing as in figure 4(c).

Cycle Assumptions

The TF and TP could be 2 or 3 spool engines depending on the desired OPR and the off-design performance desired. The RTP could be a 1 or 2 spool depending on the off-design characteristics desired. Table III details the important design point assumptions for the engines. In the case of the reference turbofan, the performance of the 2 spool versions was used. The 3 spool version was used for the TP_{50} because it gave slightly better performance at off-design conditions. Only 2 spools were necessary for the TP_{25} and the RTP_{10}.

It was assumed that for the engines with an OPR of 50, the first compressor was axial with a pressure ratio of 13.5 while the high compressor was a single stage centrifugal compressor with a pressure ratio of 3.7. This was assumed because it was felt that an axial compressor under these conditions might be rather inefficient due to small passageways.

The schedule of compressor efficiency used in this report is shown in figure 5. The efficiency of the compressor was varied to check the sensitivity of the results to these assumptions. The engine data was calculated on two engine codes; GENENG II (ref. 8), and NEPCOMP (ref. 9). Both of the codes allow full off-design performance to be calculated using component maps.

Propellers

Propeller efficiency. - Apparent propeller efficiency versus Mach number is shown in figure 6 for variable camber and conventional propellers. This schedule, from reference 10, is not theoretical performance but actual wind tunnel and flight data from the 1950's. The apparent efficiency varies depending on the blockage of the cowl behind the propeller. The greater the blockage from the cowl, the better the apparent propeller efficiency. This is because apparent efficiency is really a measure of the force on the propeller shaft. The cowl causes some back pressure on the propeller which is measured as a positive or forward force on the propeller while no account is made of the drag force on the front of the cowl. Real efficiency takes this cowl or (blockage) effect into account.

When the cowl is nonexistent (cowl is the same size as the hub of the propeller) the worst efficiency shown for the variable camber propeller at Mach 0.80 is 0.784. Along this curve, apparent efficiency would be the same as real efficiency. The trend with Mach number is quite severe near Mach 0.80. The bad performance here is mainly due to the thick hub of the propeller being exposed to the high Mach numbers.

As cowl size is increased, the hub of the propeller sees a turning flow field and a lower relative Mach number. Thus, as figure 6 shows, the apparent propeller efficiency is improved. Variable camber propellers have been tested with large cowls which resulted in apparent propeller efficiency as high as 0.952 at Mach 0.80. In a rigorous installation study, the cowl weight and pressure drag penalty of larger nacelles would have to be weighed against the improved efficiency which a larger cowl allows the propeller to have. In this study the real propeller efficiency was assumed to be 0.85 at all Mach numbers from 0.65 to 0.90. At Mach 0.80 the propeller efficiency was varied from 0.78 to 0.95 to see the effect on TP performance. This is the range shown in figure 6 for the variable camber propeller at Mach 0.80 with a range of cowl sizes.

There were several other ways that a propeller efficiency of 0.85 was arrived at as the reference for Mach 0.80. Examining old data, it was found that the small cowl used in figure 6 was sized to represent a typical Electra cowl. It was also found that the cowl drag effect amounted to about 0.04 in propeller efficiency. So if 0.04 is subtracted from the apparent efficiency in figure 6 at Mach 0.80, the real efficiency would be about 0.827 if it was a variable camber propeller or 0.843 if it was the conventional propeller referred to in the figure.

Looking at Electra propeller data it was found that an Electra type propeller in front of an Electra type nacelle could be made to give a real efficiency of 0.78 today at Mach 0.80. Applying supercritical technology to that propeller would raise the efficiency to about 0.81. Since most of the propeller high speed losses are in the hub region, it was felt that the advanced propeller weight technology assumed in this study would lead to a thinner propeller shank in the hub region. This can only increase the propeller efficiency above the 0.81 value already estimated. Exactly what efficiency the propeller might achieve remains to be seen, but a value of 0.85 would not appear to be an unreasonable goal for the mid 1980's.

As was shown in figure 6, conventional propellers can achieve good performance at high speed also. This can be supported by looking back to some 1950 propellers that gave good results at high speed. By the word conventional, what is meant is that they are not variable camber. But they are not conventional from the standpoint of camber and thinness because the blades are very thin with little or no camber. Table IV gives some results from three propellers tested. The range of propeller efficiency at Mach 0.80 for the three propellers shown in the table is from 0.82 to 0.874. Thus, the 0.85 used in this study falls in this range.

Propeller diameter. - The results of this study in terms of fuel saved are not sensitive to the type of propeller assumed, only the efficiency. It was assumed early in the study that variable camber propellers would be desirable because they combine the low camber benefits at high speed with the high camber needed for good takeoff performance. Thus the costs and weights of variable camber blades were put in to the study as well as the associated diameters.

It was estimated from preliminary data that the variable camber propeller required to do the job would be over 6.7 m (22 ft). Thus the high wing aircraft seemed the best solution to ground clearance problems. More recently, Hamilton Standard has suggested that a nonvariable camber propeller might do the job as well. The authors of reference 14 indicated that this might be a 6 or 8 bladed propeller on one shaft with swept propeller tips. With 8 blades the diameter would be small enough to allow installation on more conventional low wing aircraft. The advanced technology described in reference 11 is solving the weight problems in the propeller thus allowing larger thinner blades with smaller shanks. This is the type of technology needed in order to get 8 blades on one hub.

Propeller takeoff performance. - In order to have an effective propeller at takeoff, a lot of camber is usually required. At high speed cruise the camber is undesirable. Thus the variable camber blade overcomes this difficulty. Since this aircraft was sized at high speed and high altitude, it was assumed

that the thrust lapse would be so large that takeoff would not be a problem. In fact, it was estimated that it might be desirable to reduce the throttle setting at takeoff instead of increasing it. Under these unique conditions of having more power than necessary, even more than desirable for passenger comfort, it was recognized that the high camber at takeoff might not be necessary. Thus the previously mentioned 6 or 8 bladed propeller on a single shaft may be the best solution. However, this remains to be seen and this report is based on the variable camber propeller size, weight, cost, and takeoff performance.

Propeller noise. - Propeller noise was not calculated in this study. However, reference 11 indicates that the variable camber propeller is a very quiet propeller for the range of design criteria considered. By very quiet is meant 105 PNdB or less at 152 m (500 ft). The 6 or 8 bladed conventional propeller discussed would also be quiet due to the number of blades and the subsonic tip speeds, according to the authors of reference 14.

Propeller and gearbox weight. - From propeller maps it was found that the best variable camber propellers would have to be approximately 6.7 m (22 ft) in diameter. With the propeller diameter fixed, propeller and gearbox weight was estimated from reference 11. According to reference 14, large propellers were very heavy in the 1950's as were gearboxes. This is reflected in the band of data labeled 1950's in figure 7. By the 1960's, the weight of propellers and gearboxes had been reduced by 35 to 40 percent as shown in figure 7. The latest developments in large propellers calls for fiberglass shells over a steel spar with the area between filled with foam. This, coupled with the latest integrated gearbox designs, has reduced the weight another 35 to 40 percent as shown by the band in figure 7 labeled early 70's. These levels of weight have been achieved and demonstrated with good reliability. Further advanced programs aimed at advanced fiber composites are expected to reduce the weight to the late 70's level shown in figure 7. This is the weight used in this study. Recent contact with the authors of reference 11 indicated that the late 1970's estimate would probably not be achievable until the early 80's because of lack of funding.

Turboprop heat exchanger. - It was assumed for purposes of this study that the heat exchanger used on the TP was a rotary one using a ceramic matrix material. This selection was based on in-house studies which indicated that this may be the best type of heat exchanger for TF applications. It was assumed that this would be true for TP's also. At the cruise design point, the heat exchanger was sized to give an ϵ of 0.85, a total pressure drop of 4 percent and a 2 percent leakage on the gas side and on the air side. It was further assumed that at off-design, these values did not change. This is not significant in the results because most of the fuel is consumed at cruise. These parameters are listed in table III along with the cycle assumptions of all the engines.

The weight of the matrix material comes from the thermodynamic requirements of the cycle and the material properties. The weight of the entire heat exchanger, including the matrix (W_{Hx}) was estimated to be:

$$W_{Hx},\ kg = \text{weight of matrix} + 163 + 381\ \frac{D_{matrix}L_{matrix}}{D_{ref}L_{ref}}$$

This equation is based on an in-house preliminary design study of this type of heat exchanger for a TF engine. The heat exchanger was designed to fit behind the engine. It was shaped as a hollow drum. A sketch of this is shown in figure 8. The matrix revolves slowly, exposing itself to the airstream and then to the gas stream alternately. This transfers the heat from the hot gas stream to the cold airstream. Thus, the air to the combustor is preheated and less fuel is needed to reach a given T_4. The drag of the extra large engines was accounted for.

Cost

The cost of the airframe is a function of many things. Two of the main parameters are the quantity to be produced and the airframe weight. Since all the aircraft in this study will be treated equally, the absolute number to be produced has only a second order effect. The cost of the airframe per pound is shown in figure 9. This cost is taken from the center of the band of data shown in reference 12.

The cost of the turbofan engines (C_{eng}) was estimated to be:

$$C_{eng}(1974\ \$) = 1.2\times10^6\ (\text{engine airflow}/1300)^{0.35}$$

This equation is representative of modern day high bypass ratio turbofans. It is the same equation used in reference 13.

The cost of the TP engines is broken down into parts: cost of the core, cost of the propeller and gearbox, and cost of the heat exchanger (if used). The cost of the TP core has been correlated with shaft horsepower for a large group of engines. The curve shown in figure 10 represents this correlation, in 1974 dollars. The cost of the propeller and gearbox (C_{pg}) is estimated to be

$$C_{pg}(1974\ \$) = 200\ 000(\text{propeller diameter}/6.7\ m)$$

This estimate is based on a preliminary cost estimate for a 6.7 m diameter, 6 bladed variable camber propeller, gearbox, and associated controls. The

estimate was made by Hamilton Standard, a company which has been in the propeller business for years. This makes the cost of the propeller and gearbox about 50 percent of the cost of the engine. When the cost of the entire airplane is added up, the cost for the turboprop airplanes compared to the turbofan airplanes compares very favorably to the results of the reference 2 study. For lack of any data at all, the cost of the heat exchanger was assumed to be 500 dollars per pound. This makes the heat exchanger cost per pound nearly the same as the engine cost per pound. Both of these costs were varied over a wide range to determine their effect on DOC.

Direct Operating Cost

No matter what method is used for calculating DOC, the absolute level is always in question. In this study only relative DOC is reported. Since the aircraft being compared are essentially the same except for the propulsion differences and minor size differences, relative DOC should be a good measure of the differences. In this study the 1967 ATA DOC method was used (ref. 14). However, the equations were updated to 1974 dollars. Also the engine maintenance formulas were not used. In their place the maintenance formulas developed by American Airlines (ref. 15) were used. The cost was set at 66.05 dollars/m^3 (25 ¢/gal) for the medium range mission and 92.47 dollars/m^3 (35 ¢/gal) for the long range mission. These values correspond to domestic and international price averages paid by United States airlines in December of 1974 according to the Civil Aeronautics Board (CAB). Fuel cost was varied from 52.84 dollars/m^3 (20 ¢/gal) to 132.1 dollars/m^3 (50 ¢/gal) to determine its effect on the DOC relationships.

RESULTS AND DISCUSSION

General SFC Trends

When this study was started some trends in uninstalled SFC versus Mach number were generated to scope the problem. A relatively high turbine inlet temperature of 1590 K (2960 R) was selected for all the engines at cruise. The OPR was varied from state of the art type values of 25 to advanced levels of 50. The RTP engines had their OPR optimized for SFC. On the TF's, the BPR was varied from 4 to 14. The TP's were assumed to have variable camber propellers which allowed good efficiency at high speed while maintaining good takeoff performance and low noise. The heat exchanger for the RTP's was assumed to

be an advanced ceramic rotary type with an ϵ of 0.85, a 4 percent pressure loss, and 4 percent leakage. These would all be considered advanced technology.

The results of this investigation are shown in figure 11. At Mach 0.80, the JT9D and the reference turbofan engine used in this study are spotted for reference. The top band shows the range of SFC to be expected at a BPR of 4 when OPR is varied from 25 to 50. The band width is almost constant over the range of Mach numbers investigated. The improvement in SFC is roughly 9 to 10 percent for this change in OPR. At a BPR of 14, increasing the OPR from 25 to 50 reduces the SFC by about 7 percent at Mach 0.85 and 10 percent at Mach 0.50.

The effect of BPR can be seen on the figure also. At Mach 0.85, increasing the BPR from 4 to 14 reduces the SFC by 14 and 12 percent for OPR's of 25 and 50, respectively. At Mach 0.50 the reductions are 22 percent at both OPR's.

The TP's gas generator performance is comparable to that of the TF's. But most of the thrust, and therefore, the SFC, depends on the propeller efficiency. The performance shown in this figure is for the propeller efficiency shown in figure 6. It is estimated that the performance is achievable with a 6.7 to 7.6 m (22 to 25 ft) variable camber propeller operating at sonic relative tip speed at cruise.

When the OPR's increased from 25 to 50 the TP's is reduced by 6.3 percent at Mach 0.85 and 9.7 percent at Mach 0.50. The big reduction is not so much with OPR as it is in engine type. The TP's show a reduction in SFC compared to the high BPR TF's of roughly 18 percent at Mach 0.85 and 34 percent at Mach 0.50.

The RTP's had an OPR ranging from 15 at Mach 0.50 to 10 at Mach 0.85. The performance of this engine type was only slightly better than the TP's with OPR of 50. This is a typical result and indicates that there are two ways of improving the SFC in TP engines.

The cruise Mach number selected as a reference for this study was 0.80 because that is roughly where the jet transports cruise today. The cruise Mach number was varied towards the end of the study to see the effect on fuel used, TOGW, and relative DOC. If Mach 0.80 is examined in figure 11 and everything is referred to a TF with a BPR of 4 and an OPR of 25, the gains in SFC are as follows. Increasing BPR to 14 reduces the SFC by 15 percent. Increasing the OPR to 50 on the BPR-14 engine reduces the SFC another 7 percent. If a TP is used with an OPR of 50, the SFC is reduced another 20.5 percent. The optimum RTP engine reduces it another 2.5 percent. So the total potential is about 39 percent. It does not follow that the potential savings in fuel, TOGW or DOC is exactly 39 percent. These quantities must be determined by theoretically flying the installed propulsions systems on a representative aircraft and mission. The rest of this study reports the results of this mission analysis.

Fuel and TOGW Comparisons at Mach 0.80

In order to make comparisons, there must be a reference. Unless otherwise stated, the reference engine in this study was a turbofan with a BPR of 10.4 and an OPR of 40. The complete cycle assumptions for the reference engine are given in table III. The cycle was chosen because of its optimum fuel consumption characteristics as described in reference 6 for a noise goal of FAR-10 dB. The reference TF was made compatible with the TP's in this as table III shows. It was then flown in the same flight code and with the same ground rules and on the same missions as the TP's so it wo ld be compatible in every respect and thus be a valid reference (ref. 10).

The actual fuel burned on the mission is shown in figure 12 versus engine sea-level-static airflow. The reference engine is shown as the circled points. One purpose of plotting versus engine airflow is to find the tradeoff in SFC versus engine size. This usually occurs because of the bucket in the SFC versus thrust curves at cruise. In the case of high BPR TF's and TP's, this bucket does not occur. A reduction in power is immediately accompanied by an increase in SFC. Therefore, this type of trade cannot be made. The smallest engine that will do the job is the lightest and has the best SFC. (Takeoff thrust is not a constraint due to the high thrust lapse.) So the only reason to plot versus engine airflow is to show the slope of the curves, to show the penalty for oversizing an engine to gain more performance potential, and to show the penalty incurred in building a common size engine for a medium and long range airplane.

The end points marked by a hash mark (the smallest engines as determined by cruise drag) are the points to be initially compared in figure 12. Referring to the circled point on the long range airplane, a TP_{25} reduces fuel used by 31.5 percent, a TP_{50} by 33.2 percent, and the RTP_{10} reduces it another 1.6 percent. Since either the TF_{50} or the RTP_{10} have about equal potential, practical considerations outside the scope of this report will be required to determine which is the best system.

The same engine type was chosen for the reference for the medium range mission also. Compared to that point, the TP_{25} reduces fuel used by 27 percent, the TP_{50} by 28.3 percent, and the RTP_{10} reduced it another 1.6 percent.

To give an example of how common engine size penalties can be evaluated, assume that the reference TF is chosen for the long range mission. The required airflow would be 356 kg/sec (785 lb/sec). If the same size reference TF engine were used on the medium range airplane, the fuel consumed would be 22 000 kg, which is an increase of 4 percent from the fuel used at the minimum size engine. With this figure and any following figures where engine size is one of the coordinates, this type of trade may be made.

The gains for the TP engines compared to the reference TF engine is significant. But it should be recalled that the comparison is against an advanced TF where the BPR is 10.4. If the reference TF in this study were compared to a JT9D or a CF6 type engine on the same aircraft, the reference TF would have saved 22 percent in fuel already according to reference 6. In addition, the cruise L/D ratio of the reference aircraft at Mach 0.80 was 18.6 in this study. Modern wide body aircraft, such as the 747, achieve levels of L/D around 16 at Mach 0.80. So the aircraft type used in this study already represents a fuel savings capability of about 15 percent for any given engine type. Therefore, the TP_{50} in this study is estimated to reduce the fuel-per-passenger mile by 52 to 56 percent for medium and long range missions, respectively, compared to a modern BPR 5 to 6 engine on a modern wide bodied jet. About 85 percent of this reduction is due to the engine type and the rest is due to the airplane differences.

The TOGW is shown in figure 13 versus engine size. Looking at the end points of the curves, it is seen that when OPR is increased from 25 to 50 on any of the TP engines, the TOGW increases slightly. So the added weight of the higher OPR engines in conjunction with the larger engine size, must just about offset the fuel saved. TOGW is reduced significantly, however, when a TP is used instead of the reference TF. For the long range mission the TP reduces the TOGW by as much as 16 percent compared to the TF powered aircraft. On the short range mission the reduction in TOGW is as much as 10 percent. The RTP_{10} engine does not reduce the TOGW compared to the best TP at long range and is between the TP_{25} and the TP_{50} at medium range. No important conclusions are suggested by such small changes at this preliminary stage.

Summary of Weights and Costs at Mach 0.80

Tables V and VI summarize the weights of major items such as fuel, propulsions system, wings, landing gear, airframe, and so forth. Table V is for the medium range mission and table VI is for the long range mission. The lower TOGW of the TP's compared to the TF's is reflected in the cost of the aircraft (less engines). The costs for the TP's airframe are as much as 5 percent less and the propulsions system costs are about 30 percent less than for the reference TF. These lower costs, plus lower fuel bill cost, add up to lower DOC for the TP's. The DOC is reduced about 14 percent on the medium range mission and by 18 percent on the long range mission by the use of TP's instead of the reference TF. The RTP has higher initial cost than the regular TP's due to the heat exchanger. On the medium range mission the DOC is reduced by only

5 percent and on the long range mission 11 percent by the RTP's compared to the reference TF.

The gains for the TP's in DOC are impressive, but are they realistic? It is believed that they are. The lower airframe costs should be correct since the airplanes are lighter. The engine, propeller, and gearbox purchase costs are reasonable and documented as well as can be expected at this early stage. The one thing that could be undefined is the engine maintenance cost. It was assumed in this study that the engine maintenance cost would be calculated the same for a TP as for a TF. It is a function of the engine cost, weight and number of engines, plus the number of thrust reversers per engine. These are quantities which are well defined. So the only problem could come if the TP maintenance is unusual in some respects. The conclusion from reference 16 is that the TP maintenance is no worse than a TF on equal missions. In fact, it says, "A 50 percent improvement in the propeller could make the TP measurably superior to the TF in the overall record." This conclusion is the result of extensive history studies of the T-56 engine.

Sensitivity Studies

Sensitivity to propeller efficiency. - Since it would appear that the TP engines offer a significant advantage in terms of fuel and TOGW compared to the optimum high BPR TF, it would seem appropriate to examine some of the TP assumptions. The one factor that is of major importance is the propeller efficiency. So the propeller efficiency was varied over a probable range to evaluate its impact on the fuel used and TOGW.

The changes in fuel used and TOGW can be seen in figures 14(a) and (b) as propeller efficiency is varied from 0.78 to 0.96. If the propeller efficiency did fall off to 0.78 (the lowest value reported in ref. 17 at Mach 0.80) the savings in fuel and TOGW would obviously be reduced as shown in figure 14. What is also obvious from the figure is that even at this level of efficiency, the improvement in fuel and TOGW compared to the reference TF are still significant. Of course, if propeller efficiencies were greater than the reference value of 0.85, the improvements in fuel and TOGW would increase as shown in figures 14(a) and (b).

Sensitivity to compressor efficiency. - During the study there was some uncertainty whether the high compressor on the TP_{50} should be axial or centrifugal. The pressure ratio of the high compressor was 3.7. The concern was that for the small airflows being used at the high OPR level of 50, the blade heights might be very small, thus leading to low efficiency and/or surge problems. So a centrifugal compressor stage was assumed and the efficiency was degraded by 0.02

from that used for axial compressors. This penalty in efficiency was assumed based on past experience which involved the judgment of several Lewis Research Center compressor experts.

In order to determine the consequences of the efficiency assumptions for the high compressor, the efficiency was varied ±0.02 from the reference level of 0.860. The initial idea was to plot the trends in fuel used and TOGW as the efficiency was varied. However, the engine performance changed very little when the deltas were applied to the efficiency. At cruise the SFC varied less than 1 percent either way, while the thrust varied only slightly more than 1 percent. These changes were so small that the changes in fuel and TOGW were not calculated. It was felt that the tolerance in such calculations was of the same order of magnitude as the changes to be evaluated. Therefore, no meaningful results could be obtained from making such an evaluation. It is obvious that the assumptions on high compressor efficiency for the TP_{50} are not critical to the results of this study. The insensitivity is due mostly to the fact that the CPR on this engine was only 3.7.

<u>Sensitivity to customer power extraction</u>. - The core of the TP is sized in such a way that the corrected airflow is about 25 percent less than that of a TF of comparable OPR. Thus, as customer power is extracted, the TP suffers a larger change in SFC than does the TF. It was found during the study that the electrical and hydraulic needs of the aircraft could be met by taking 60 hp from each engine. This increased the cruise SFC of the reference TF and the TP_{50} by about 1.0 percent. The rest of the airconditioning, pressurization, and ventilation system requires a maximum of four times this amount of power. This would result in a maximum total power extraction of 300 hp from each engine for all needs. This would increase the cruise SFC 5.8 percent for the reference TF and 6.6 percent for the TP_{50}.

As the result of such power extraction, the fuel used and the takeoff gross weight of all the aircraft in this study would increase from what was shown in figures 12 and 13. The changes in SFC are such that the increases in fuel and TOGW would be only slightly more for the TP_{50} than for the reference TF. The TP_{50} would suffer about 1 percent more than the TP_{25}. Thus, the comparisons made between engine types and OPR's thus far, would not change significantly.

The area of customer power extraction or bleed is an area that usually gets a lot of effort in a refined study. There are certainly some tradeoffs to be made between extracting power to drive a separate system, using a completely separate system, and just bleeding engine air. No attempt was made in this study to find the optimum system. It did appear, however, that using a shaft power-takeoff system might be slightly superior to using engine bleed. In the results

reported, customer bleed and power were not included.

Sensitivity to fuel cost. - DOC is very sensitive to fuel cost. This is shown in figure 15 where relative DOC is plotted versus fuel cost. All four engines are shown on the figure and the reference fuel cost is 92.5 dollars/m^3 (35 ¢/gal). This data is for the long range mission.

As mentioned earlier the TP's reduce the DOC by about 18 percent compared to the reference TF. If fuel costs increase in the future, the DOC reductions achieved by the use of a TP will increase relative to the TF. Another way to look at it is, while higher fuel costs do drive DOC costs up, use of a TP instead of a TF could offset some or all of this increase.

Sensitivity to propeller, gearbox, and heat exchanger cost. - It is important to find the sensitivity of DOC to some of the most important cost inputs. This helps evaluate the answers reported so far.

The propeller and gearbox cost were varied plus and minus 50 percent to find the effect on DOC. It will be recalled (table VI) that the cost of the propeller and gearbox was 200 000 dollars. This estimate was obtained from Hamilton Standard, one of the major propeller and gearbox suppliers. So the plus and minus 50 percent was felt to more than cover any uncertainties. The results of varying the propeller and gearbox cost are shown in figure 16(a). It can be seen that if the cost does increase 50 percent, the DOC advantage for the TP over the TF is reduced by about 1 percent. The conclusion is that the propeller and gearbox cost input could not effect the DOC results of this study to any significant degree.

The cost of the heat exchanger is relatively unknown. In this study it was assumed to be 500 dollars per pound. As table VI showed, this resulted in a heat exchanger cost of 779 000 dollars. This cost reduces the TP advantage over the reference TF by almost 50 percent. If the cost of the heat exchanger is increased by 50 percent, figure 16(b) shows that the RTP_{10} is still better than the reference TF by about 7.5 percent. Reducing the cost of the heat exchanger 50 percent improves the DOC. However, it is still not as good as the regular TP's. What is obvious from the figure is that the heat exchanger cost would have to increase about 100 percent before it would cause excessive DOC compared to the reference TF. The merits of the RTP_{10} versus the conventional TP will have to be weighed on the bases of which is the easiest to build, or which presents the least uncertainties. No case can be made against the RTP_{10} based on fuel used or TOGW. However, if the cost of the heat exchanger is very much at all, the DOC as calculated in this study would indicate a disadvantage for the RTP_{10} compared to the regular TP's.

Fuel, TOGW, and Relative DOC Comparison Versus Mach Number

The final figures 17 and 18 show the effect of design cruise Mach number on fuel used, TOGW, and DOC. Each Mach number represents a slightly different airplane as discussed in the section "METHOD OF ANALYSIS." The design altitude and wing loading were held constant at all speeds. The other aircraft parameters were varied with Mach number in a reasonable manner as discussed in the METHOD OF ANALYSIS section. However, an optimum configuration for each Mach number is beyond the scope of this report. The trends shown in figures 17 and 18 are believed to be correct nevertheless.

The results are shown in figure 17 for the medium range mission. Figure 17(a) shows a rather constant relationship in fuel used between the TF and TP's at all speeds. The TF is nearing a minimum fuel used at a Mach number below 0.65. The TP's minimum is obviously at a lower Mach number. The RTP_{10} was not flown at other speeds. It is expected that the curve for the RTP_{10} would follow the shape of the other TP curves. The TF shows a tendency to find a minimum TOGW in figure 17(b) at a Mach number of 0.65 while the TP's minimum must be at a lower speed. The trends of all the engines are consistent with each other and no crossovers are observed. The relative TOGW's differences established at Mach 0.80 between different engine types are held fairly constant at speeds above Mach 0.80. Below this speed, the TP's are improving faster than the TF. In figure 17(c) the DOC of both TF's and TP's have a minimum between Mach 0.75 and 0.80. The DOC spread between TF's and TP's is about constant at all speeds.

On the long range mission, the airplanes are a little more sensitive to changes in speed. Figure 18(a) shows there is a minimum fuel used by the TF at a Mach number of about 0.725. The TP's are approaching a minimum also at about Mach 0.60. The RTP_{10} is shown on figure 18(a) also. It was not flown at Mach numbers other than 0.80. This was because no significant case could be made for or against this concept at Mach 0.80. There is no reason to believe that this situation would change at the other Mach numbers studied in this report.

The TOGW trends are plotted in figure 18(b). The TF has a minimum around Mach 0.70. No TOGW advantage was found for TP engines with an OPR of 50 instead of 25 at any Mach number. The TP's are superior to the TF at all Mach numbers. The curve is not affected by Mach number as much as the TF's. This is mainly due to the constant propeller efficiency assumed in the study. If the propeller efficiency had tapered off at high speed, all the TP curves in figures 17 and 18 would have been higher on the right end and lower on the left end. The RTP_{10} still has TOGW the same as the TP_{25} in figure 18(b).

The DOC curves in figure 18(c) show that at about Mach 0.775, the TF and the TP's have a minimum. The difference established between the TF and the TP's at Mach 0.80 is held fairly constant at other Mach numbers. The RTP_{10} is slightly worse than the regular TP's at all Mach numbers. This is due to the cost of the heat exchanger.

Remedies For Turboprop Deficiencies

Any time a TP aircraft is considered in a study such as this, many questions arise. Past early experience with the Viscount and the Electra have left the impression that TP aircraft are inferior to TF aircraft. They flew slower, had poor high altitude climb performance, a bumpy ride, a high level of cabin noise and vibration, and early experience showed poor reliability in the propeller systems and the gearboxes. All of these problems are listed in table VII. Listed also are the causes of the problems, probable remedies, and technology needed to solve the problems. Most of the objections to the earlier TP's are valid, but with improved design, better technology, and the proper sizing for high altitude high speed cruise, most of the problems should be alleviated.

CONCLUSIONS

The fuel savings potential of advanced turboprops (operational by 1985) was calculated and compared with that of an advanced turbofan for use in an advanced subsonic transport. The figure of merit was fuel consumed. However, takeoff gross weight (TOGW) and direct operating cost (DOC) were also calculated. All the engines used a cruise design turbine-inlet-temperature of 1590 K (2960 R) at an altitude of 10.67 km (35 000 ft) and Mach 0.80. However, the design Mach number was varied from 0.65 to 0.90. Overall compressor pressure ratios (OPR) of 25 and 50 were considered on the TP's. The RTF used an optimum OPR of 10 to 15. The TF had a bypass ratio (BPR) of 10.4 and an OPR of 40 which is optimum for fuel conservation. The RTP used a rotary ceramic heat exchanger with an effectiveness of 0.85, a pressure drop of 4 percent and a leakage of 4 percent. All the TP's used variable camber propellers with an efficiency of 0.85 at all flight speeds.

Two missions were used, 5500 km (3000 n. mi.) and 10 200 km (5500 n. mi.). The payload was fixed at 18 144 kg (40 000 lb or 200 passengers). Once the aircraft was designed with a wing loading of 5980 N/m^2 (125 lb/ft^2), the wing and landing gear were varied as engine size and TOGW changed. The drag of the various engine types was accounted for. The aircraft was designed to have a

L/D ranging from 20 at Mach 0.65 to 16 at Mach 0.90. At the reference Mach number of 0.80 the L/D was 18.5.

The study indicated substantial improvements in fuel used, TOGW and DOC when the TP's were used instead of the reference TF. On the long range mission, the TP's saved 31 to 33 percent in fuel and for the medium range mission, the savings was 28 percent. The TP's reduced the TOGW substantially also. On the long range mission, they reduced the TOGW 15 percent and on the medium range mission 11 percent. The DOC was also reduced by the use of TP's compared to the same reference TF. At long range, the reduction in DOC was 18 percent and at medium range it was 14 percent.

The TP engines with the OPR 50 generally saved more fuel than the ones with OPR 25. However, they caused the TOGW to increase slightly. The effect of OPR on DOC was about the same as it was on TOGW. The gains for high OPR are probably a little more than indicated in this study because the optimum OPR is somewhere between 25 and 50. It was shown in other TF studies that the optimum is near 40. However, it is flat enough that the OPR 50 engines in this study are very close to optimum.

The main conclusion of this study is that TP's offer significantly greater fuel savings, lower TOGW's and DOC's than the best fuel conservative TF in the 1980's. The TP's in this study were estimated to reduce the fuel per passenger mile by 52 and 56 percent for medium and long range missions, respectively. This is compared to a JT9D or CF6 type engine on a modern wide bodied aircraft. About 85 percent of this reduction is due to the engine type and the rest is due to the airplane differences. About the only item that could significantly effect the fuel savings of the TP is the propeller efficiency. A reduction of 5 percent in the fuel savings would result if the propeller efficiency is reduced from 0.85 to 0.80. This is about the minimum efficiency anticipated by the 1980's. The advanced TF could lose some of its gains also if things like the bypass stream direct pressure losses are not minimized. This is very important for a high bypass engine but has no impact on a TP. Other items such as component efficiencies would tend to have the same effect on a TF and a TP. Thus their relative difference would be expected to remain about the same, which means the TP would still save about 28 to 33 percent of the fuel that an advanced TF would use.

The RTP's studied generally did as well as the regular TP's in terms of fuel and TOGW. But in most cases they actually had higher DOC than the regular TP's because of the heat exchanger cost. There was never enough improvement in fuel or TOGW to say definitely that the RTP's are better than the regular TP's. A refined design study would have to be done to determine the relative risk of the two concepts and the final cost of the heat exchanger.

It is anticipated that with advanced technology, improved design in the aircraft as well as the engine, along with proper sizing of the propulsion system for high altitude and high speed, most of the objections to the earlier turboprop aircraft will be alleviated. New types of propellers having 6 to 8 blades on one shaft, using low tip speeds, supercritical aerodynamics, super light weights, and swept tips could brighten the picture even more. Such propellers would be expected to combine good performance at cruise and at takeoff with low noise levels. The diameters of such propellers would allow them to be used on low wing aircraft.

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TABLE I. - BASIC AIRCRAFT DRAG INPUT DATA

Cruise Mach number	0.65	0.70	0.75	0.80	0.85	0.90
AR	11.7	11.3	10.8	9.4	8.1	6.9
t/c side of body	0.210	0.195	0.180	0.164	0.145	0.120
t/c tip	0.160	0.147	0.103	0.080	0.080	0.080
Leading edge sweep, deg	3.0	6.0	15.3	27.4	37.9	45.5
Taper (tip cord/root cord)	0.33	0.33	0.33	0.33	0.33	0.33
Camber	0.07	0.07	0.07	0.07	0.07	0.07
Wing loading, N/m^2	5980	5980	5980	5980	5980	5980
Cl_0	0.06	0.06	0.06	0.06	0.06	0.06
Supercritical wing	Yes	Yes	Yes	Yes	Yes	Yes

TABLE II. - TYPICAL AIRPLANE WEIGHT BREAKDOWN FOR THE LONG RANGE AIRCRAFT DESIGNED FOR MACH 0.80 USING THE REFERENCE TURBOFAN ENGINES

Structure weight, kg	35 711	Operating items, kg	7 225
Wing	14 057	Flight crew (3)	231
Horizontal tail	1 974	Cabin crew (7)	413
Vertical tail	1 143	Crew baggage	150
Body	10 069	Brief cases and navigation	45
Landing gear	5 538	Unusable fuel	153
Nacelle struts	1 024	Oil	91
Nacelles	1 906	Emergency equipment	23
Propulsion system weight, kg	7 356	Passenger accommodations	4 912
4 Installed engines	5 309	Cargo containers	1 207
Accessories	153	Operating empty, kg	65 869
Controls	72	Usable fuel, kg	54 429
Starting system	83	Payload (200 passengers), kg	18 144
Fuel system	716	Cargo, kg	0
Thrust reversers	1 023	Takeoff gross weight, kg	138 462
Fixed equipment weight	15 597		
Instruments	339		
Surface controls	2 148		
Hydraulic systems	600		
Pneumatic systems	410		
Electrical systems	986		
Electronics	727		
Flight deck accommodations	410		
Passenger accommodations	6 790		
Cargo accommodations	1 056		
Emergency equipment	614		
Air conditioning	975		
Anti-icing	160		
Auxiliary power unit	382		

TABLE III. - CYCLE ASSUMPTIONS AT THE CRUISE DESIGN POINT

Engine types	Ref. TF	TP_{25}	TP_{50}	RTP_{10}
Inlet pressure recovery	1.0	1.0	1.0	1.0
Overall pressure ratio	40	25	50	10
Fan pressure ratio	1.6	-----	-----	-----
Low compressor pressure ratio	-----	1.85	13.5	-----
High compressor pressure ratio	25	13.5	3.7	10
Efficiency of the propeller	-----	0.85	0.85	0.85
Cruise turbine-rotor-inlet temperature, K	1615	1634	1634	1634
Adiabatic efficiency of:				
Fan	0.86	-----	-----	-----
Low compressor	-----	0.892	0.86	-----
High compressor	0.85	0.86	0.860	0.865
All turbines	0.90	0.90	0.90	0.90
Efficiency at combustor	1.0	1.0	1.0	1.0
Turbine cooling bleed, percent of compressor air	8.0	10.0	11.8	10.0
C_v, nozzles	0.98	0.98	0.98	0.98
Pressure loss, $\Delta P/P$				
Fan duct	0.02	-----	-----	-----
Combustor	0.06	0.06	0.06	0.06
Turbine exit guide vanes	0.012	0.012	0.012	0.012
Heat exchanger cold side	-----	-----	-----	0.02
Heat exchanger hot side	-----	-----	-----	0.02
Heat exchanger leakage, $\Delta W/W$				
Air side	-----	-----	-----	0.02
Gas side	-----	-----	-----	0.02
Heat exchanger effectiveness	-----	-----	-----	0.85
Number of spools	2	2	3	2
BPR	10.4	-----	-----	-----
Altitude, km	10.67	10.67	10.67	10.67
Mach number	0.80	0.80	0.80	0.80

TABLE IV. - TYPICAL 1950 CONVENTIONAL PROPELLER DATA

Propeller	Mach number	Tip Mach	Efficiency	Reference
$T_1C_1P_2$	0.60	1.05	0.885	(a)
	.70		.880	
	.75		.861	
	.80		.820	
	.90	1.20	.720	
SS 8	0.70	1.05	0.876	(b)
	.80	1.05	.874	
	.90	1.20	.763	
$T_1C_1P_1$	0.60	1.05	0.839	(c)
	.70		.850	
	.75		.850	
	.80		.824	

[a]United Aircraft Corporation Internal Report R-25665-2.
[b]United Aircraft Corporation Internal Report R-24102-12.
[c]United Aircraft Corporation Internal Report R-25665-2.

TABLE V. - COMPARISON OF ENGINE TYPES AT MACH 0.80 ON A MEDIUM RANGE MISSION OF 5500 KM (3000 N. MI.)

Engine types	Ref. TF	TP_{25}	TP_{50}	RTP_{10}
Weights, kg				
TOGW	97 105	87 096	90 828	88 419
OEW (less propulsion system)	47 060	45 769	46 240	45 935
Wing	9 800	8 909	9 231	9 023
Landing gear	3 884	3 484	3 633	3 536
Other	33 376	33 376	33 376	33 376
Propulsion system	5 675	4 106	7 699	5 973
Installed engines	5 675	2 643	6 067	1 907
Propeller and gearbox	------	1 463	1 632	1 534
Heat exchanger	------	------	------	2 532
Payload (200 passengers)	18 144	18 144	18 144	18 144
Design point fuel load	26 226	19 144	18 745	18 367
Fuel used	21 145	15 422	15 161	14 821
Reserve fuel	5 081	3 655	3 584	3 546
Initial costs, 10^6 $ (1974)				
Complete aircraft	15.042	13.199	13.485	16.945
Aircraft (less engines)	9.673	9.447	9.447	9.476
Each complete engine	0.921	0.613	0.651	1.327
Bare engine	0.921	0.413	0.451	0.429
Propeller and gearbox	------	0.200	0.200	0.200
Heat exchanger	------	------	------	0.698
Spares	1.685	1.300	1.351	2.161
Direct operating cost, ¢/seat/km				
DOC	0.84	0.72	0.73	0.80
Relative DOC	1.00	0.85	0.87	0.95

TABLE VI. - COMPARISON OF ENGINE TYPES AT MACH 0.80 ON A LONG RANGE MISSION OF 10 200 KM (5500 N. MI.)

Engine types	Ref. TF	TP_{25}	TP_{50}	RTP_{10}
Weights, kg				
TOGW	138 462	115 386	118 825	115 793
OEW (less propulsion system)	58 533	55 316	55 783	55 371
Wing	14 057	11 764	12 093	11 802
Landing gear	5 538	4 615	4 753	4 632
Other	38 938	38 937	38 937	38 937
Propulsion system	7 356	4 666	8 638	6 789
Installed engines	7 356	2 990	6 716	2 222
Propeller and gearboxes	-------	1 676	1 922	1 742
Heat exchanger	-------	-------	-------	2 825
Payload (200 passengers)	18 144	18 144	18 144	18 144
Design point fuel load	54 429	37 260	36 260	35 489
Fuel used	47 259	32 436	31 569	30 820
Reserve fuel	7 169	4 824	4 691	4 669
Initial costs, 10^6 \$ (1974)				
Complete aircraft	17.556	15.199	15.544	19.327
Aircraft (less engines)	11.628	11.088	11.166	11.097
Each complete engine	1.006	0.663	0.713	1.455
Bare engine	1.006	0.463	0.513	0.476
Propeller and gearbox	-------	0.200	0.200	0.200
Heat exchanger	-------	-------	-------	0.779
Spares	1.904	1.459	1.526	2.410
Direct operating cost, ¢/seat/km				
DOC	1.14	0.940	0.95	1.01
Relative DOC	1.0	0.82	0.83	0.89

TABLE VII. - TURBOPROP COMPLAINTS

Complaint	Cause	Probable remedy	Technological problems
Slow speed	Designed that way for short range. Poor propeller efficiency at high speed.	Design for high speed. Use supercritical tehcnology, ultra-light propellers and variable camber if necessary.	None - Use high AR wing and supercritical wing. R&D needed to complete work already started or planned.
Poor climb at high altitude	Engines were sized for takeoff and/or low speed, low altitude conditions. Also propeller efficiency fell off at high speed.	Size at high speed, high altitude, and use the right propeller.	None.
Bumpy ride	Low wing loading and low cruise altitude.	Use normal (high) wing loading and high altitude cruise.	None.
Cabin noise and vibration	Propellers were never synchronized completely. A large amount of tail buffeting by propeller wake.	Propeller synchronization is a must. Simple, cheap, and light sound absorbing materials used in fuselage walls. Get tail out of wake. Use more blades per propeller.	None - Synchronization has been done by the Navy on long range patrol aircraft with great success. Probably cannot use low tail design.
High maintenance cost, especially on gearbox	Early learning curve.	Better gearboxes are available now which are smaller, lighter, and use floating gears.	None - Some R&D is needed. The old gearboxes were extremely reliable after some time in service; however, lighter propellers will help.
Passenger appeal	All of the above complaints.	All of the above remedies plus lower ticket prices allowed by lower DOC	None - If the speed, ride, quality, and noise are OK and the ticket price is down.
Emotionalism	All of the above complaints caused by bad experiences in comparison to the turbojet aircraft.	Understand the reasons for the complaints and that these reasons are no longer valid.	None - However, some people remember the problems with turboprops. They must be re-educated.

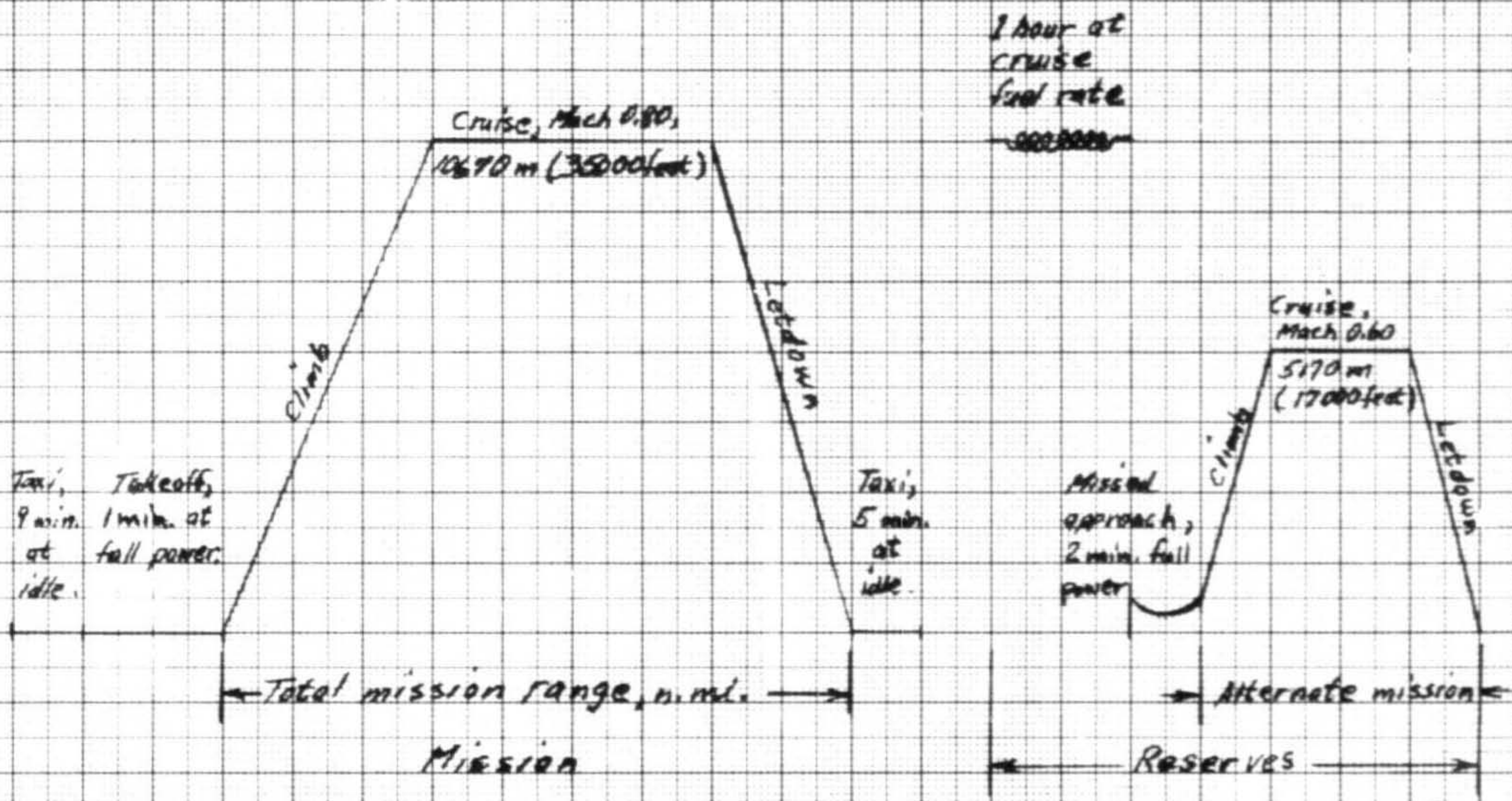
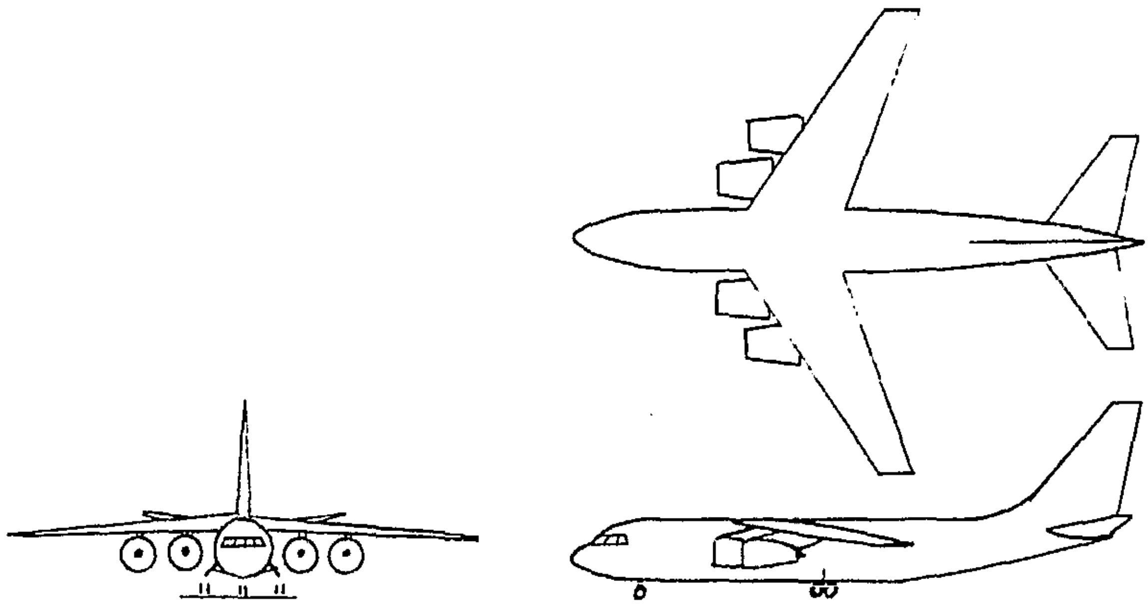
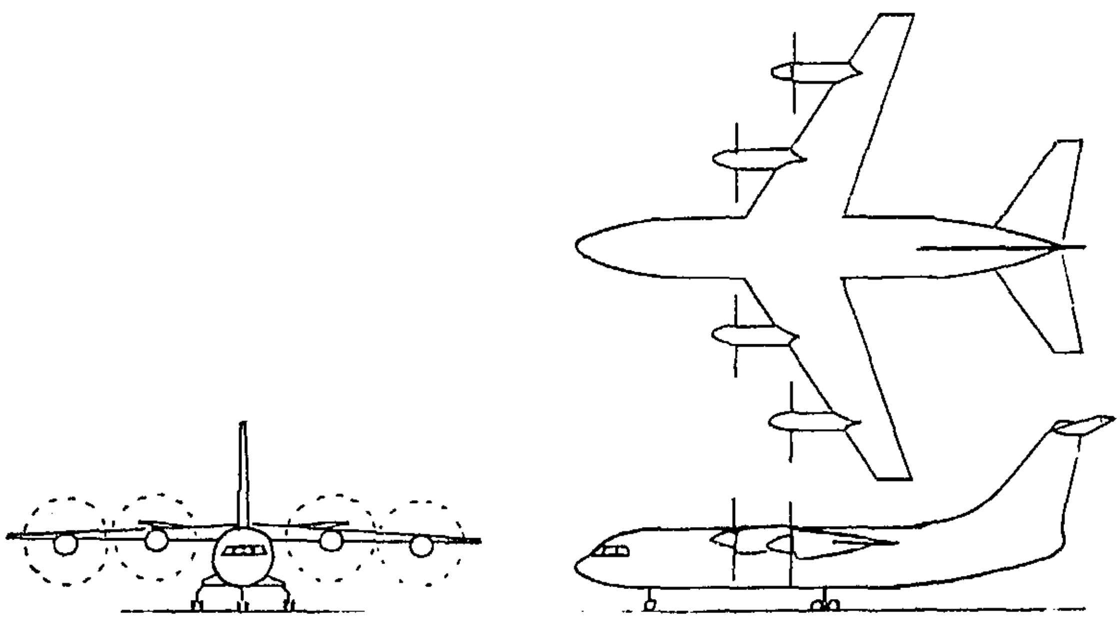


Figure 1.- Mission and reserve assumptions.



a) Turbofan powered reference aircraft



b) Turboprop powered aircraft

Figure 2.- Aircraft type sketches

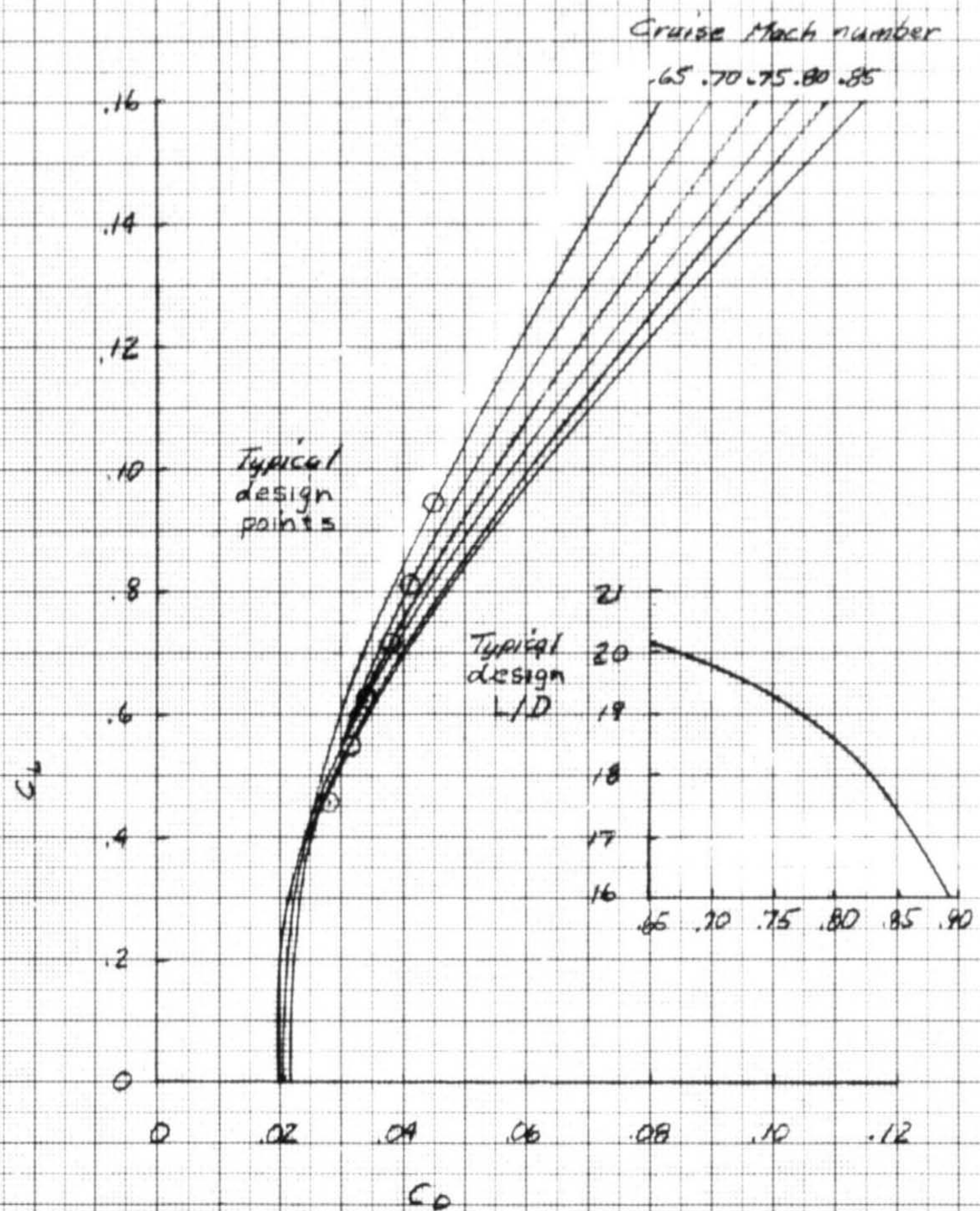
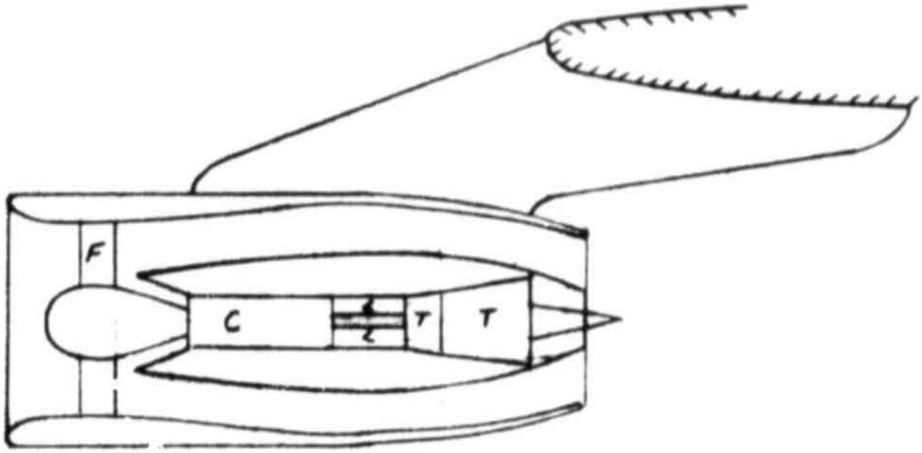
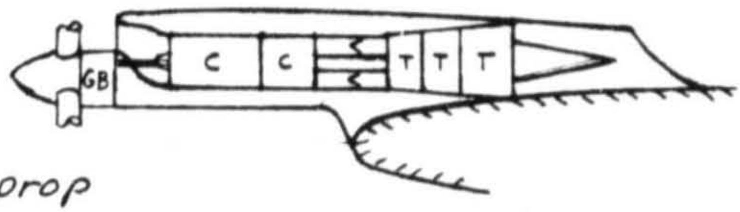


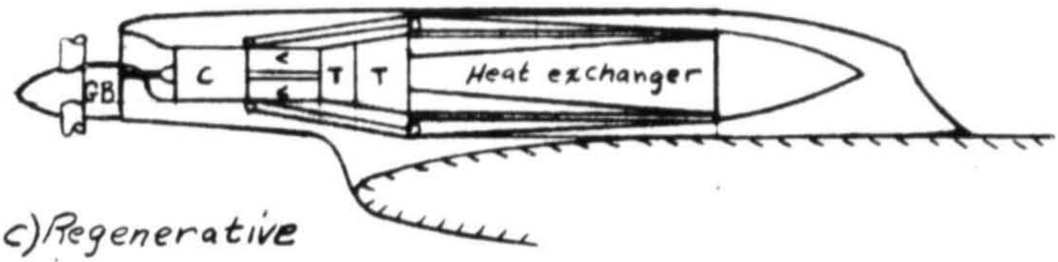
Figure 3.- Drag polars for long range aircraft.



a) Reference turbofan



b) Turboprop



c) Regenerative turboprop

Figure 4.- Engine type sketches.

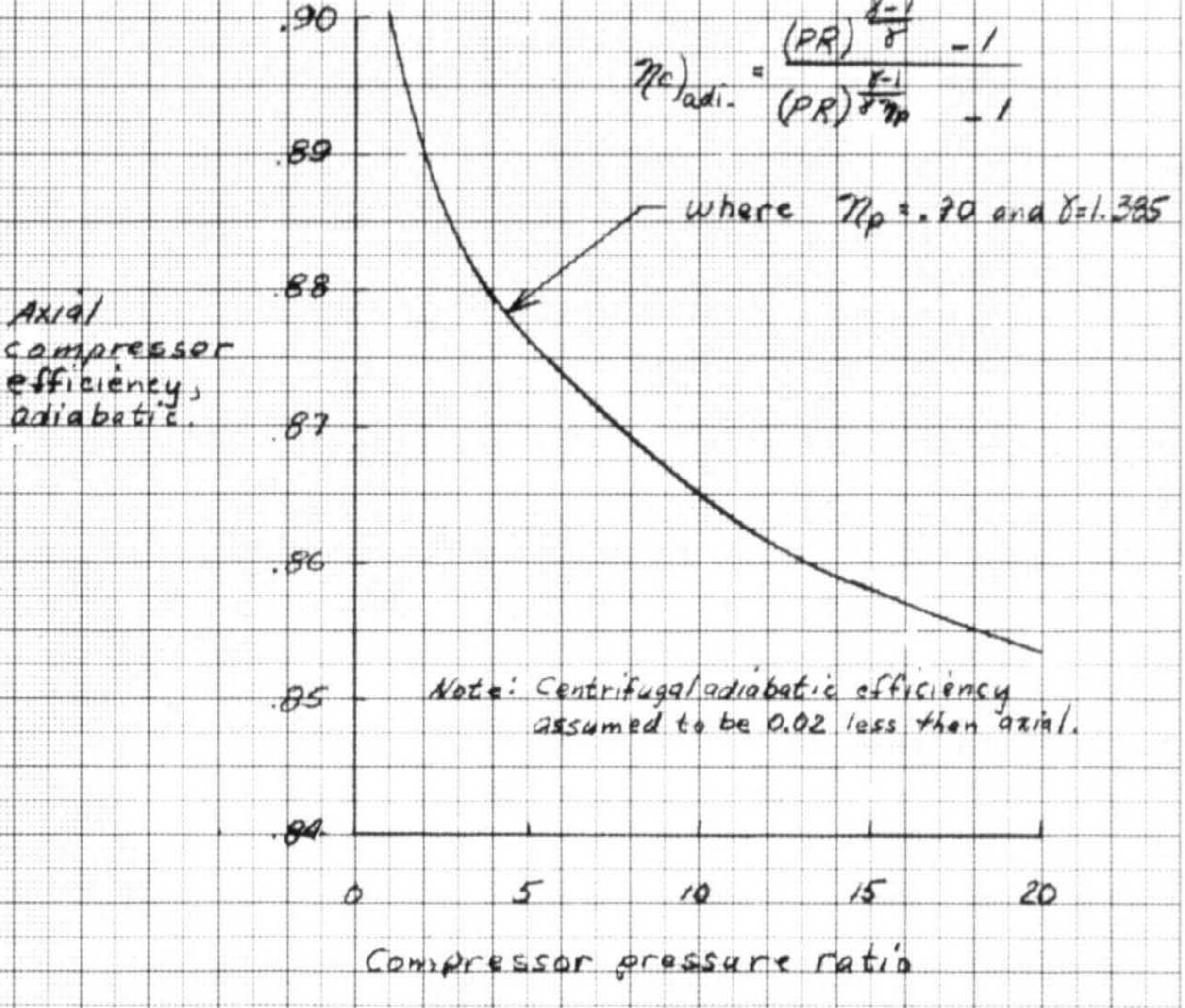


Figure 5.- Compressor adiabatic efficiency Versus Compressor pressure ratio.

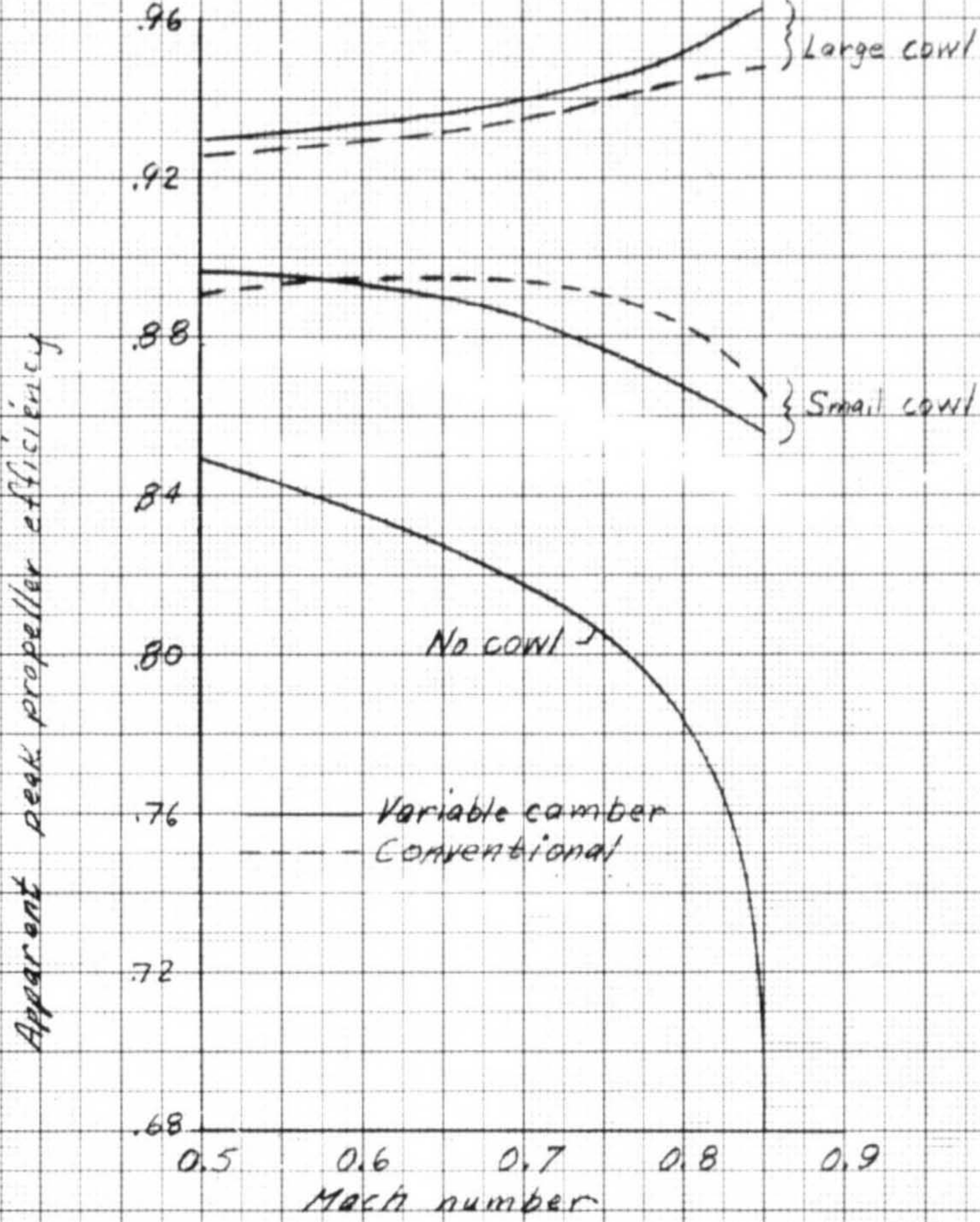


Figure 6. - Propeller performance versus design cruise Mach number.

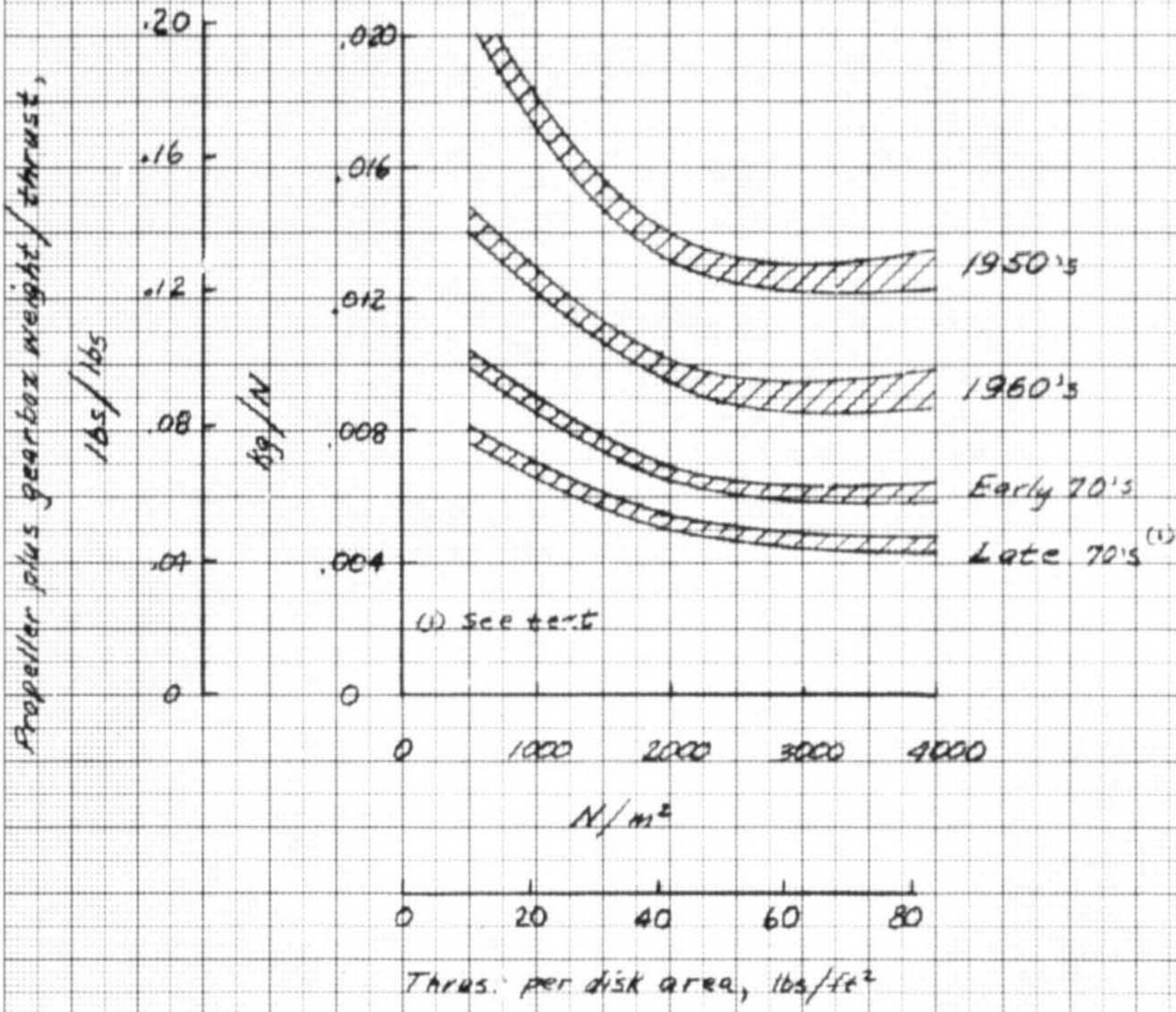


Figure 7. - Variable camber propeller and gearbox weight.

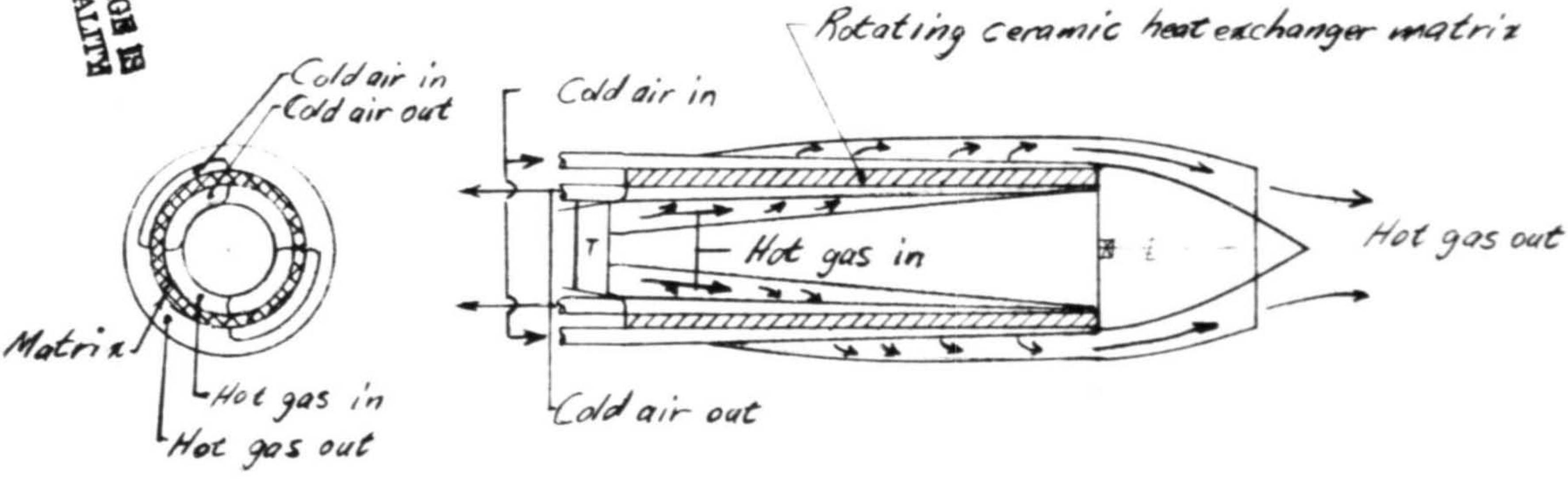


Figure 8.- Sketch of rotating ceramic heat exchanger.

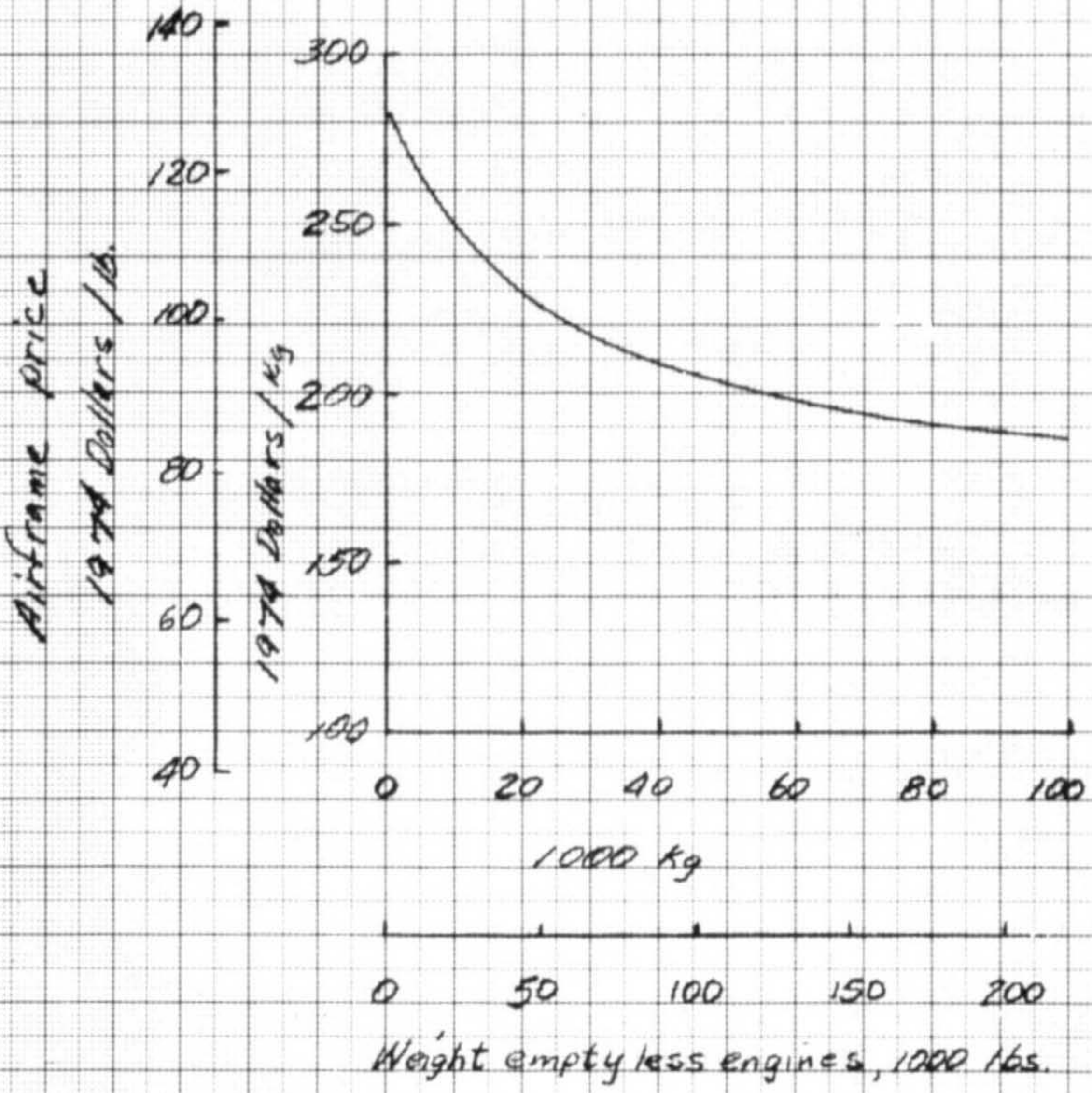


Figure 9. - Airframe price versus weight

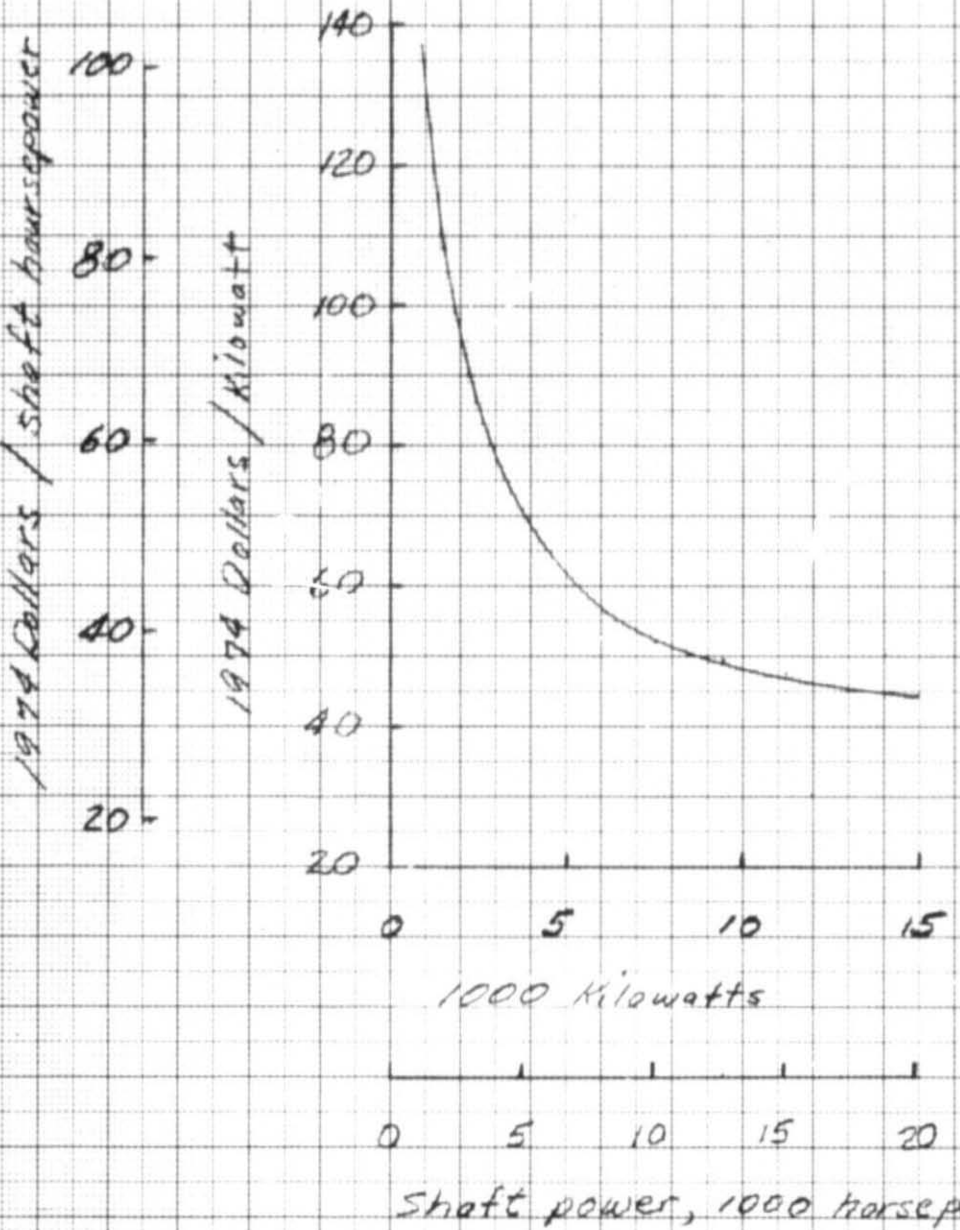


Figure 10. – Cost of turboprop gas generator in 1974 Dollars versus sea-level-static shaft power.

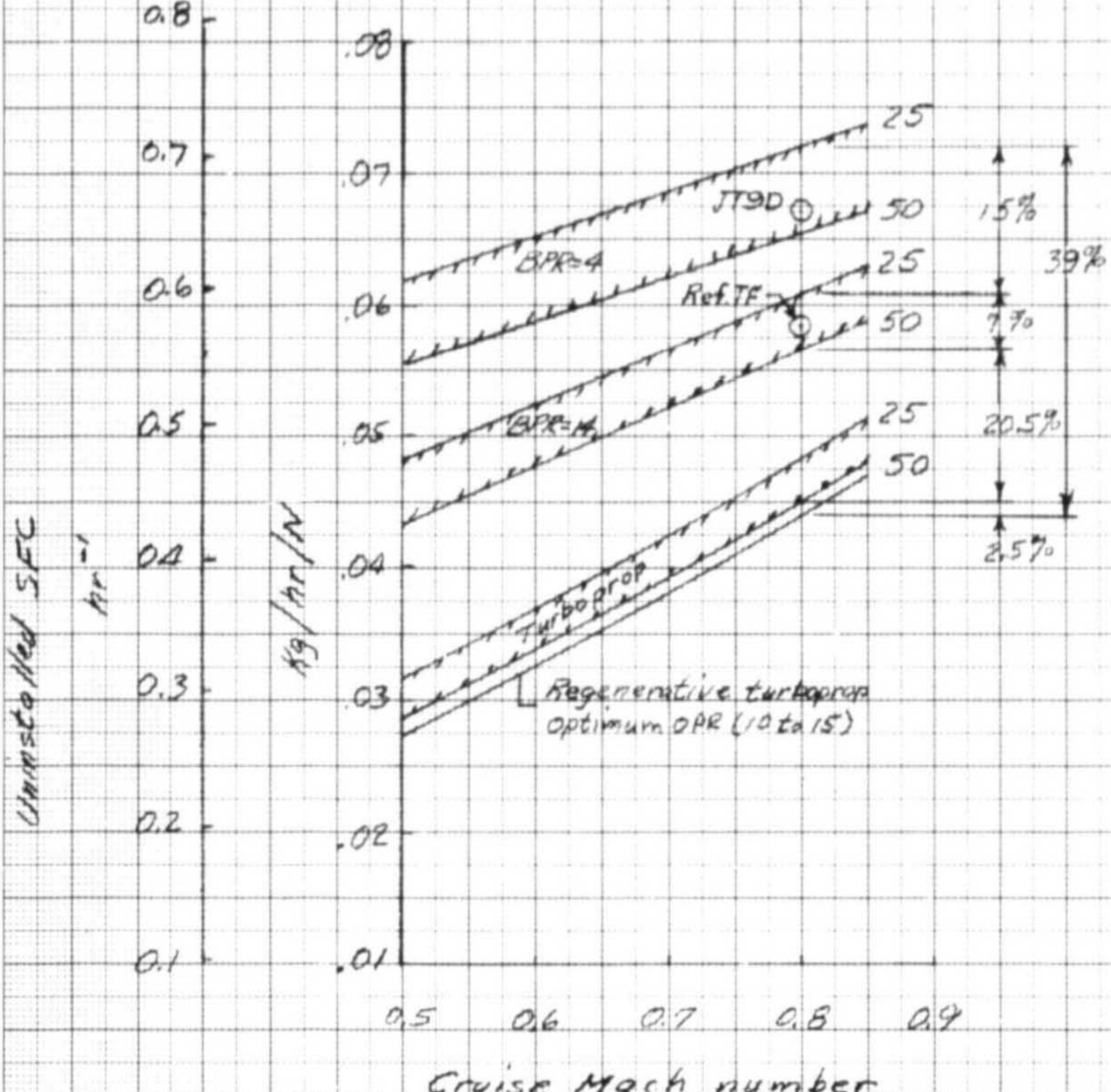


Figure 11.- SFC trends versus Mach number for several engines. Turbine inlet temperature 1645°K (2960°R), optimum FPR, 10 percent turbine cooling bleed, altitude = 10660m (35000ft.)

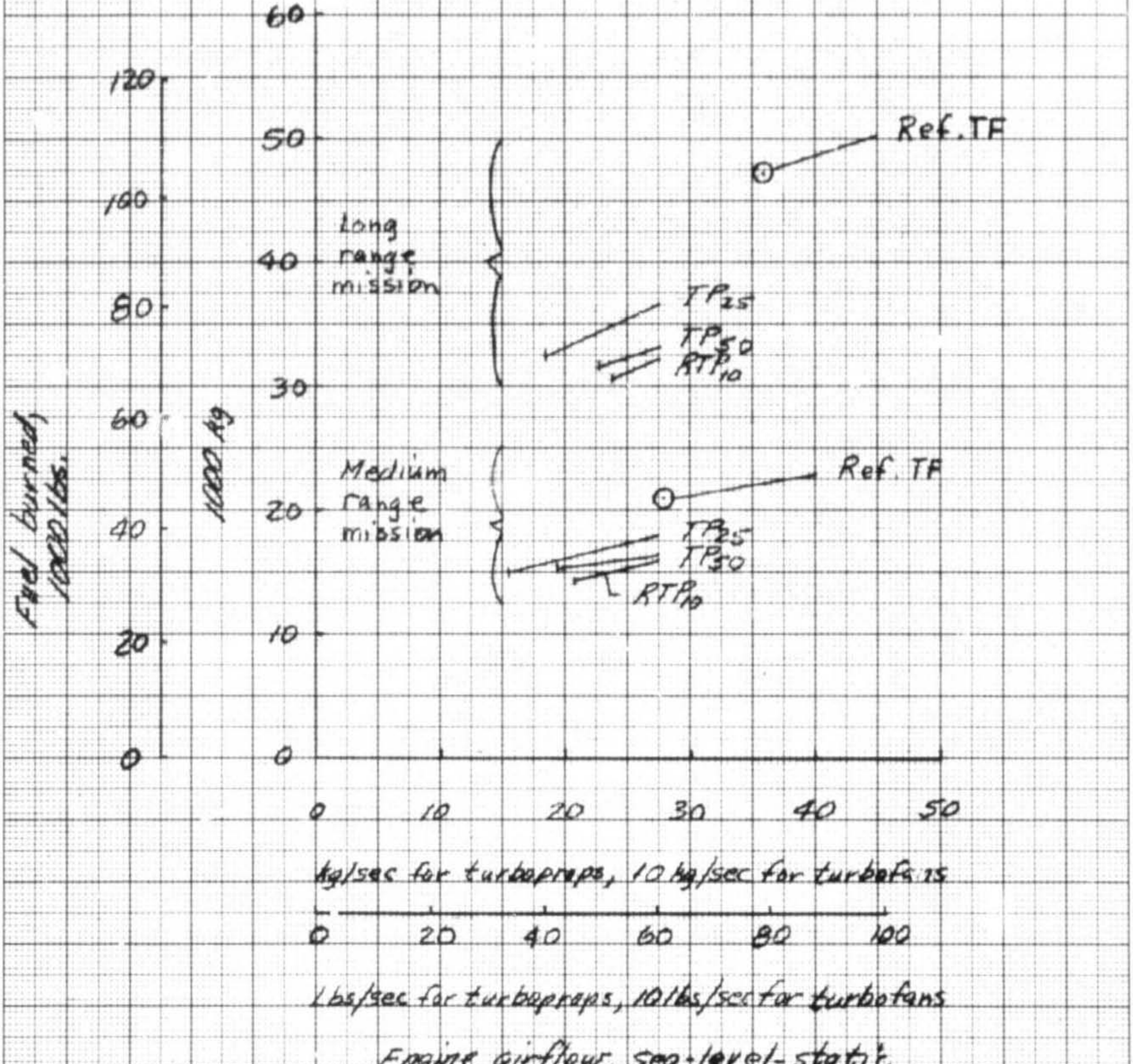


Figure 12.- Fuel burned versus engine size. Mach 0.80 design.

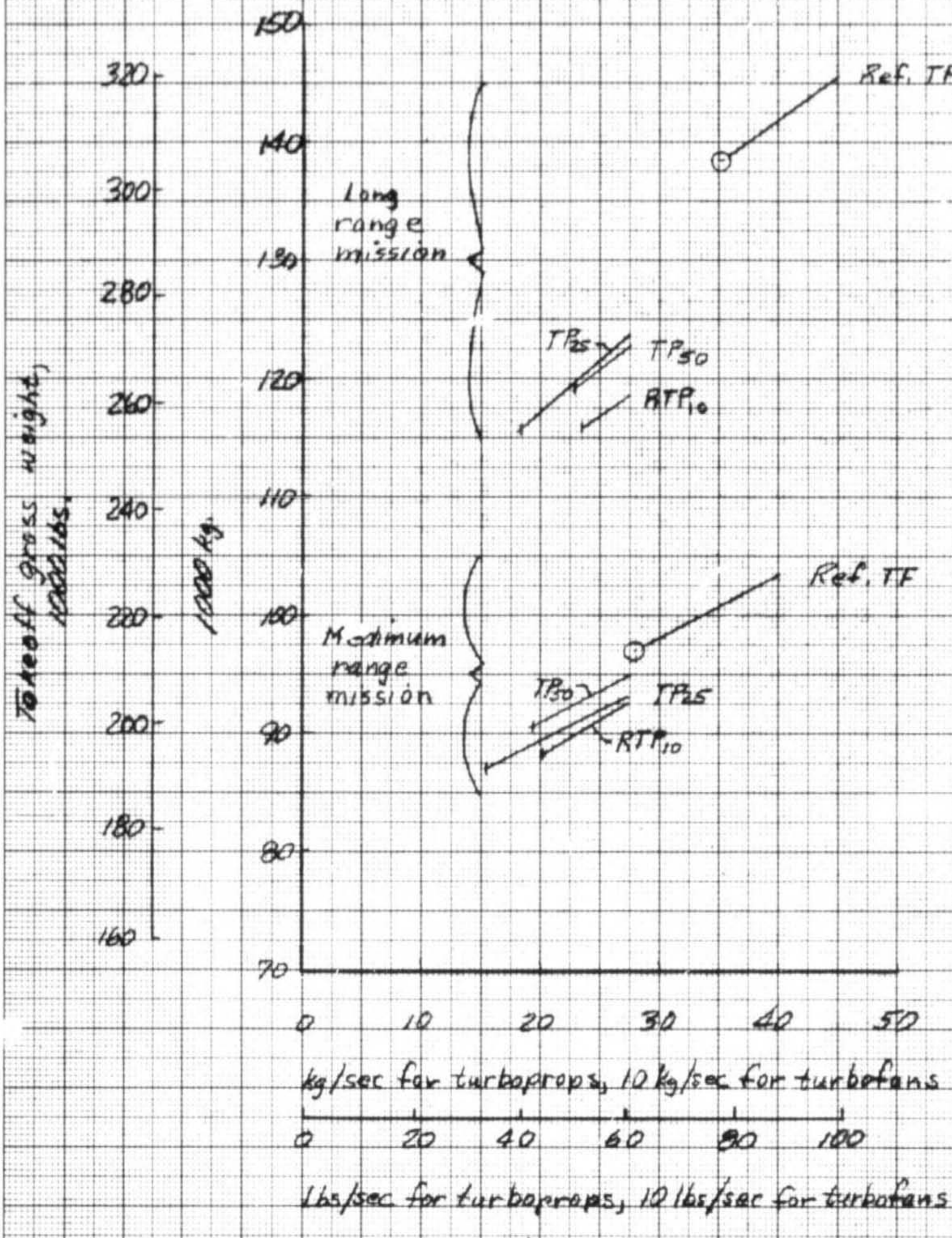
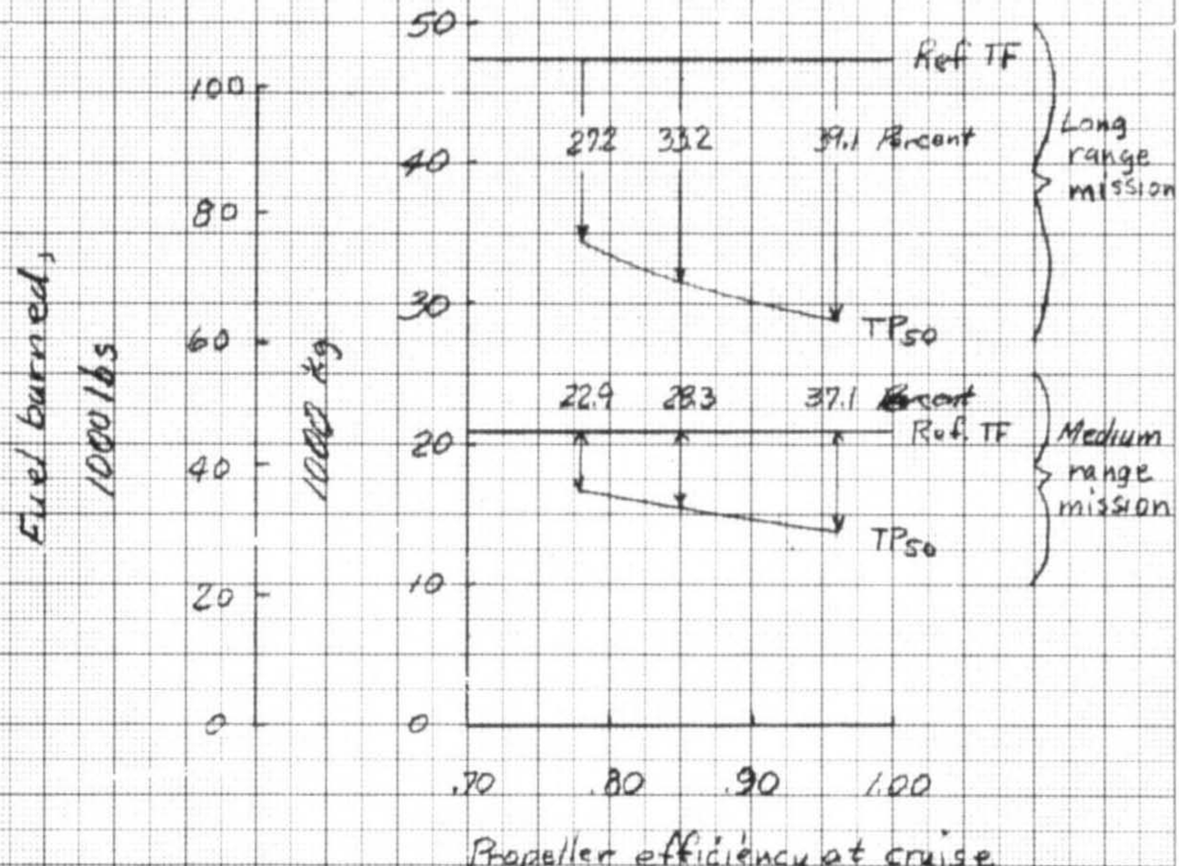
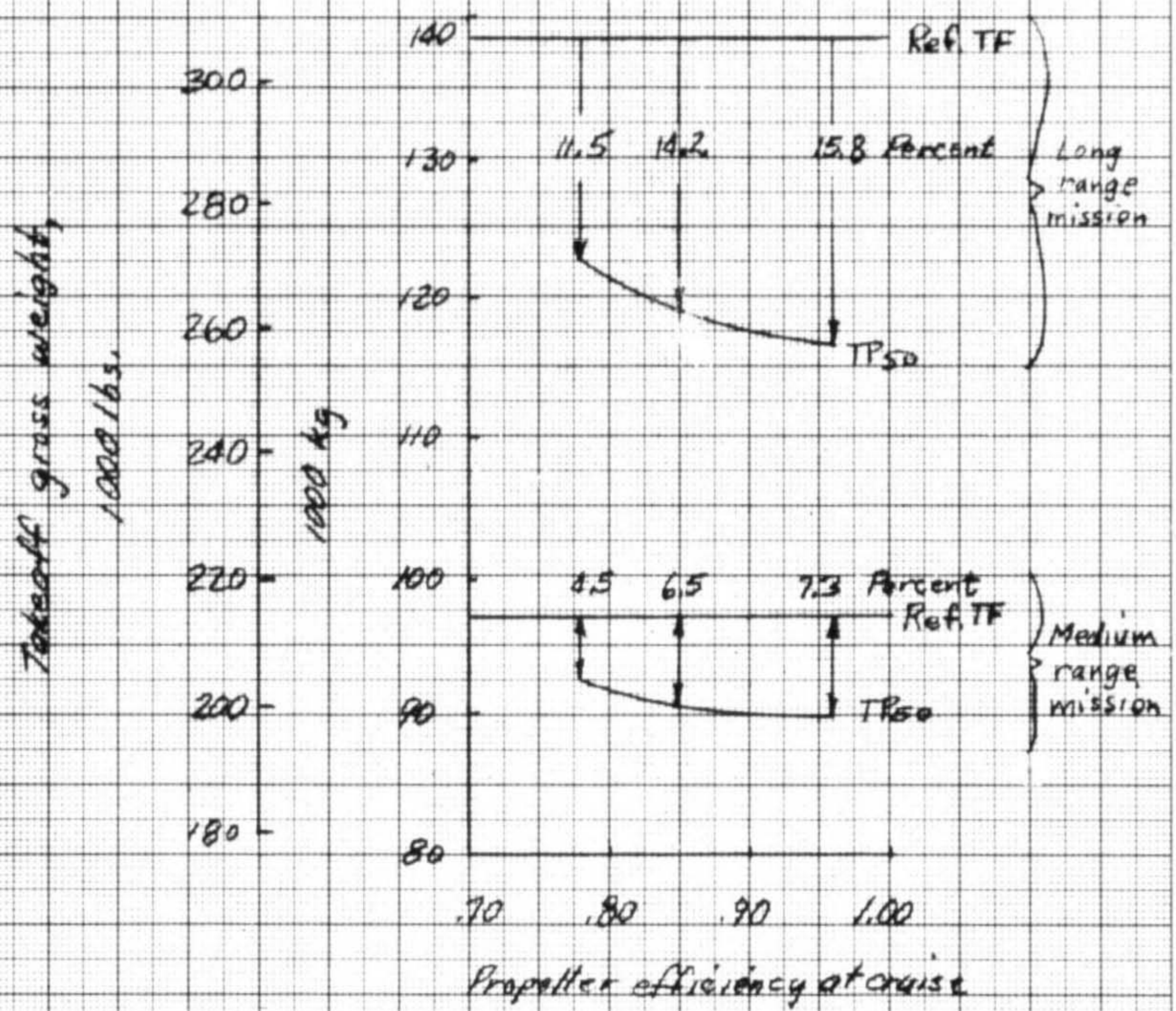


Figure 13.- Takeoff gross weight versus engine size. Mach 0.80 design.



a) Fuel burned

Figure 14.- Effect of propeller efficiency on fuel used and TOGW



b) Takeoff gross weight

Figure 14. - Cont.

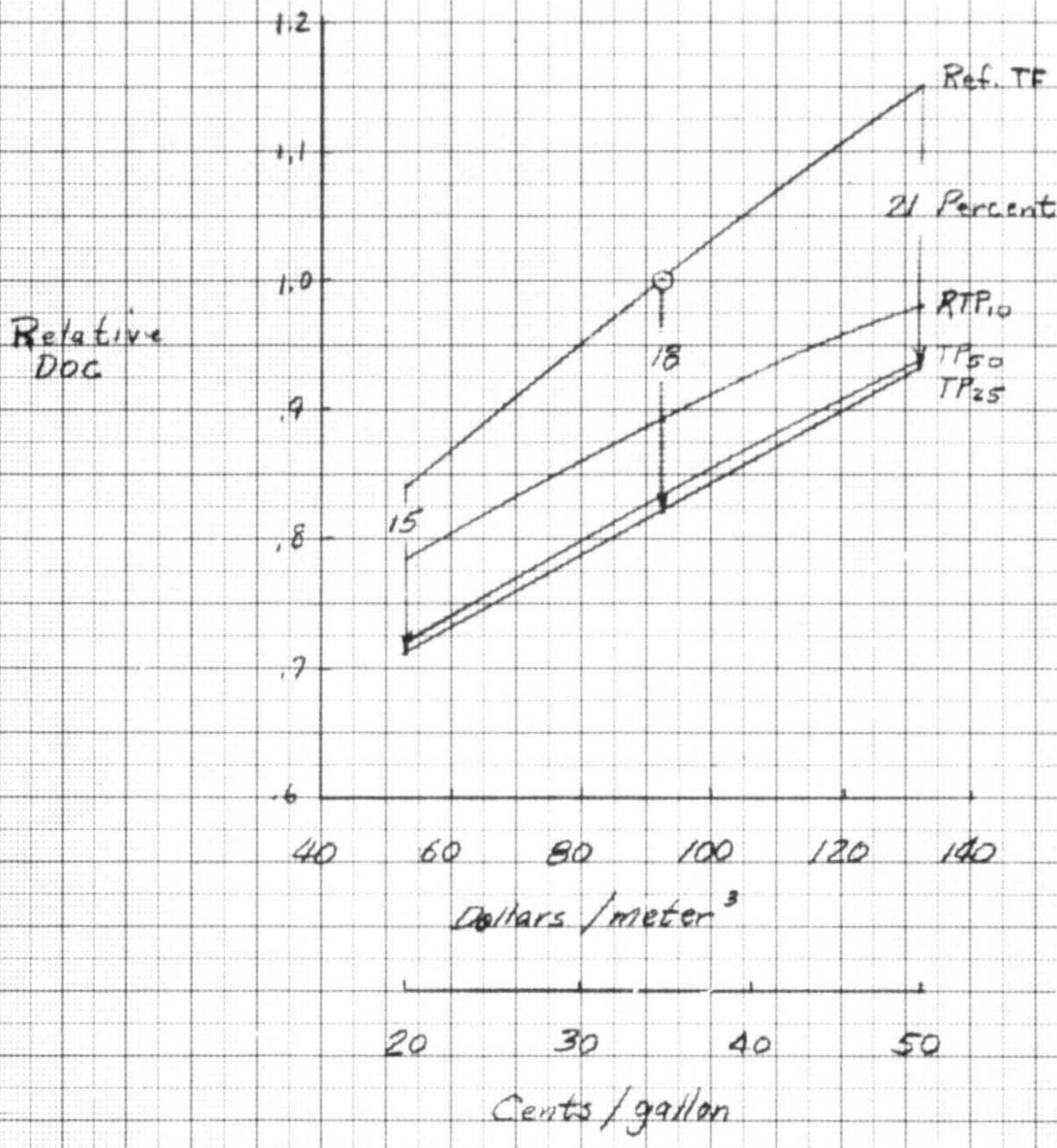


Figure 13.– The effect of fuel price on DOC. Long range mission.

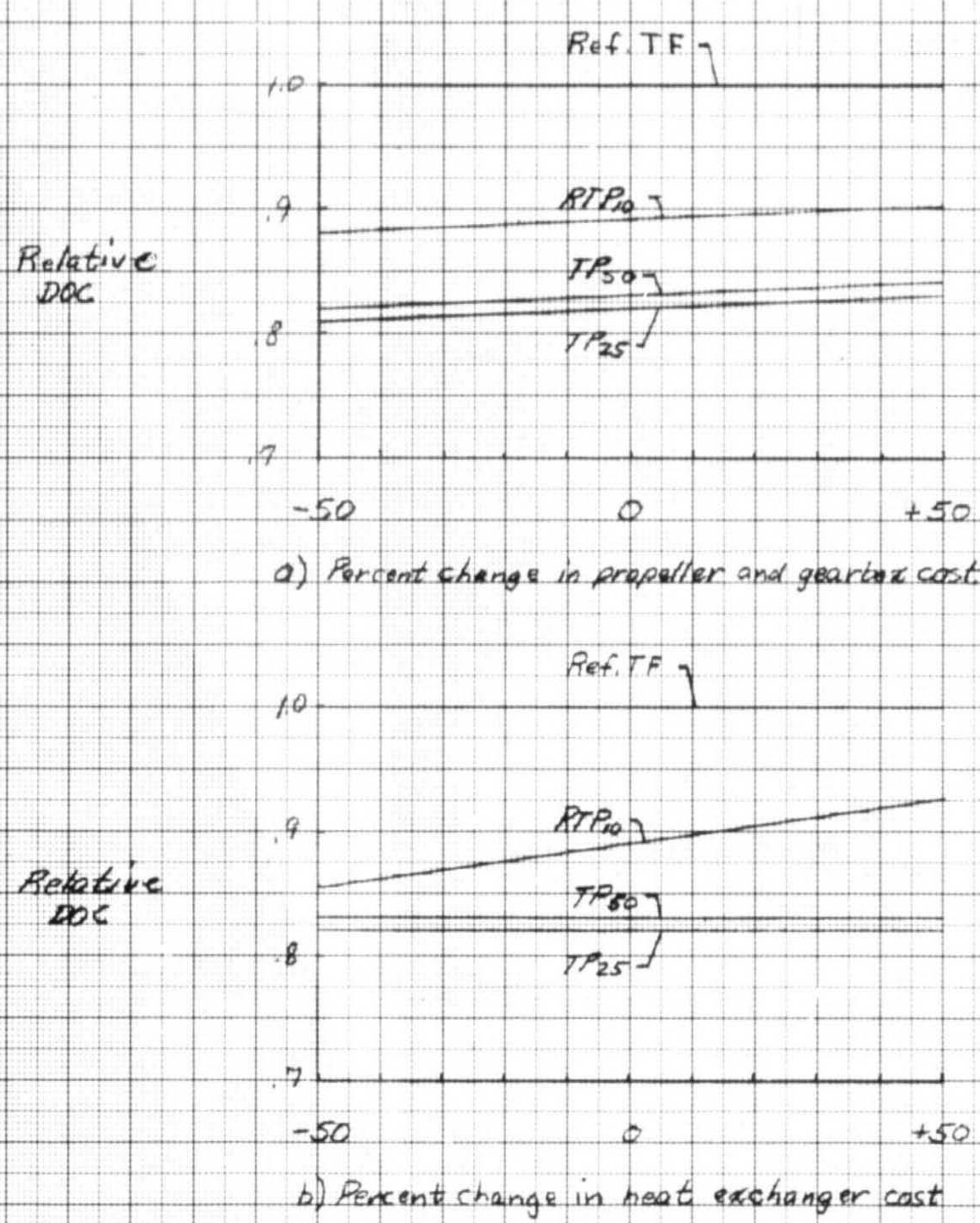


Figure 16.- The effect of propeller, gearbox, and heat exchanger on DOC. Long range mission.

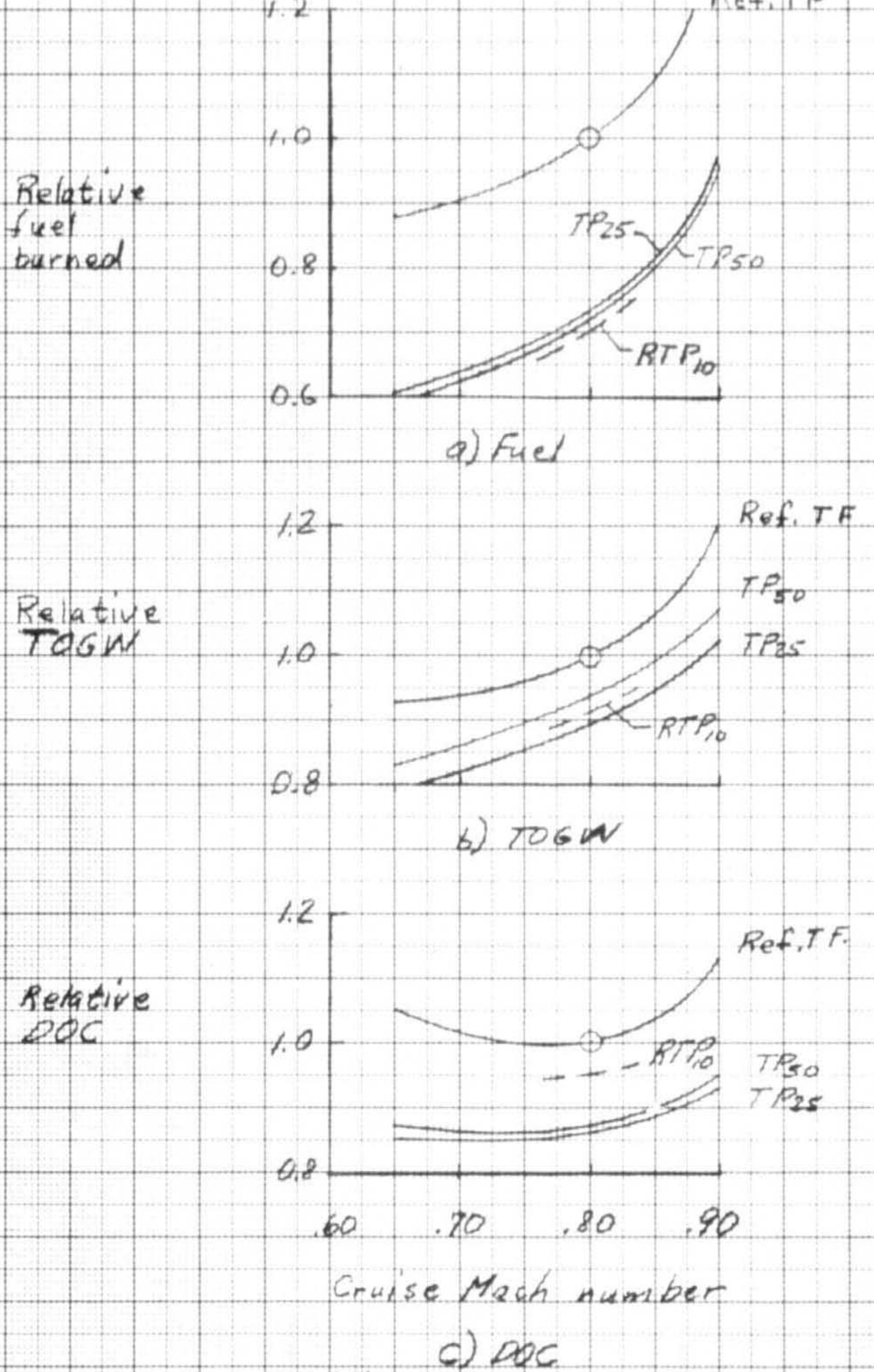


Figure 17.- Relative fuel, TOGW and DOC versus cruise Mach number. Medium range mission.

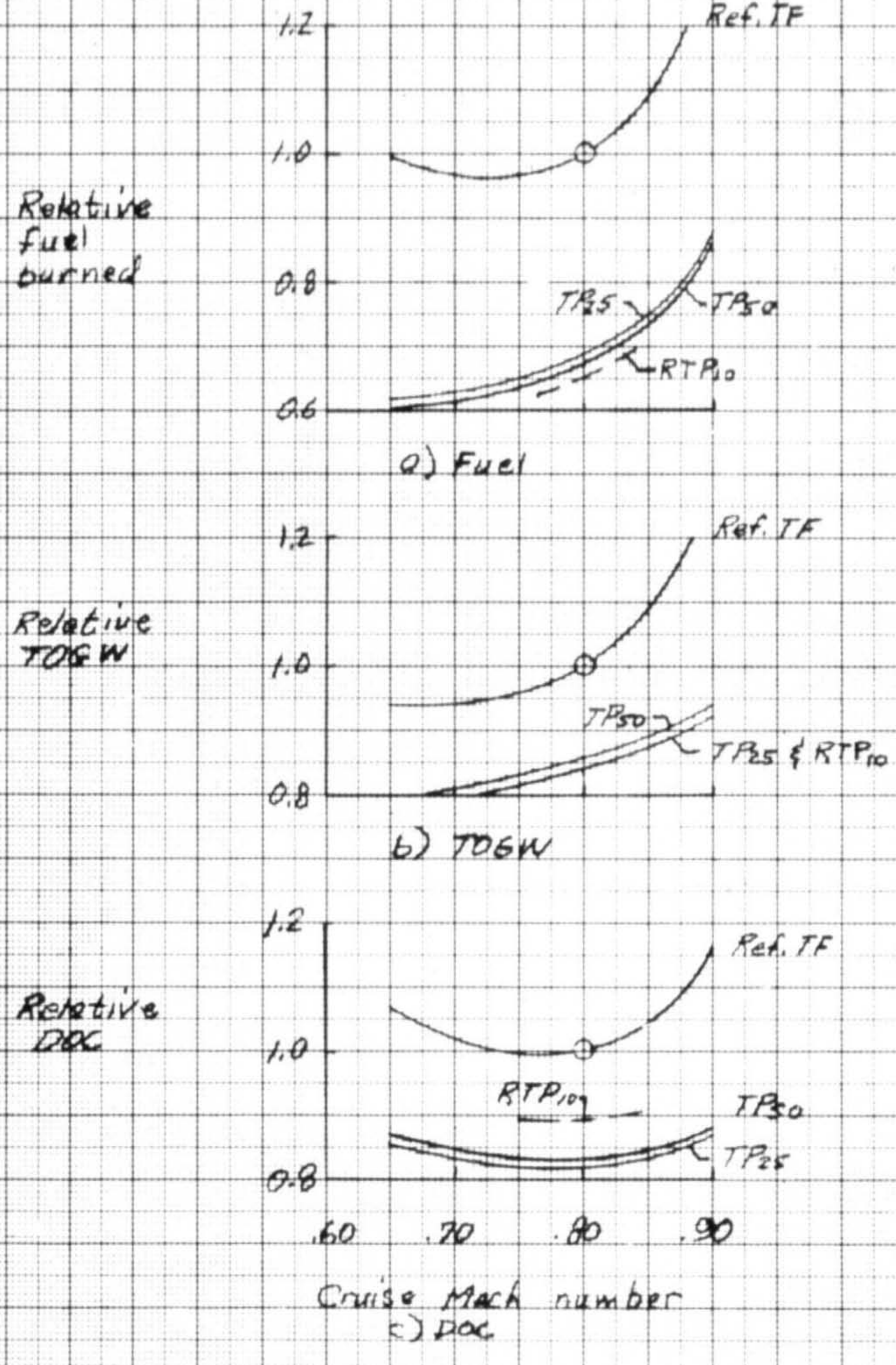


Figure 18.- Relative fuel, TOGW and DOC versus cruise Mach number. Long range mission.